SUSTAINABLE LAND IMAGING (SLI) ARCHITECTURE STUDY
Interim Status Briefing

Opening Statements

Stephen Volz
Associate Director for Flight Programs
NASA Earth Science Division
April 1, 2014

Agenda

Time (EDT)	Topic	Speaker
8:30-9:00	Check-in	
9:00-9:05	Opening Statements	Steve Volz Associate Director for Flight Programs NASA Earth Science Division Tim Newman Program Coordinator for Land Remote Sensing U.S. Geological Survey
9:05-9:15	Introduction & Overview	Del Jenstrom, Architecture Study Team Manager NASA Goddard Space Flight Center
9:15-9:20	Science Introduction	Jeff Masek NASA Goddard Space Flight Center
9:20-9:35	USGS User Needs Assessment	Jim Nelson USGS Earth Resources Observation & Science Center
9:35-9:55	Imaging Performance Characteristics	Jeff Masek NASA Goddard Space Flight Center
9:55-10:10	Representative Instrument Concepts	Phil Dabney NASA Goddard Space Flight Center
10:10-10:25	Architecture Assessment Process	Tony Freeman NASA Jet Propulsion Laboratory
10:25-10:50	Summary of Initial Findings	Evan Webb NASA Goddard Space Flight Center
10:50-11:00	Remaining Study Plans	Del Jenstrom, Architecture Study Team Manager NASA Goddard Space Flight Center
11:00-12:00	Q&A	All

SLI Study Direction to NASA

Administration Direction

In FY14 NASA will initiate the definition of a sustained, space-based, global land imaging capability for the nation, ensuring continuity following LDCM. Near-term activities led by NASA, in cooperation with USGS, will focus on studies to define the scope, measurement approaches, cost, and risk of a viable long-term land imaging system that will achieve national objectives. Evaluations and design activities will include consideration of stand-alone new instruments and satellites, as well as potential international partnerships. It is expected that NASA will support the overall system design, flight system implementation, and launch of future missions, while USGS will continue to fund ground system development, post-launch operations, and data processing, archiving, and distribution.

- President's FY2014 Budget release for NASA

Delivery Date Aug 15, 2014

- This study direction was affirmed in the January 2014 appropriations, with some comments from the Congress
- Beginning with $30 million in FY14 for NASA to study options for a future sustained land imaging system, in collaboration with USGS.
- The study shall define a <u>system for sustained global land-imaging</u> multispectral and thermal infrared information for an approximately 20-year period starting in 2018.
- The study should provide options which consider various weightings of near-term capability, continuity/gap risk mitigation, and technology infusion over the system's lifetime.

Three Basic Tenets for the SLI Program

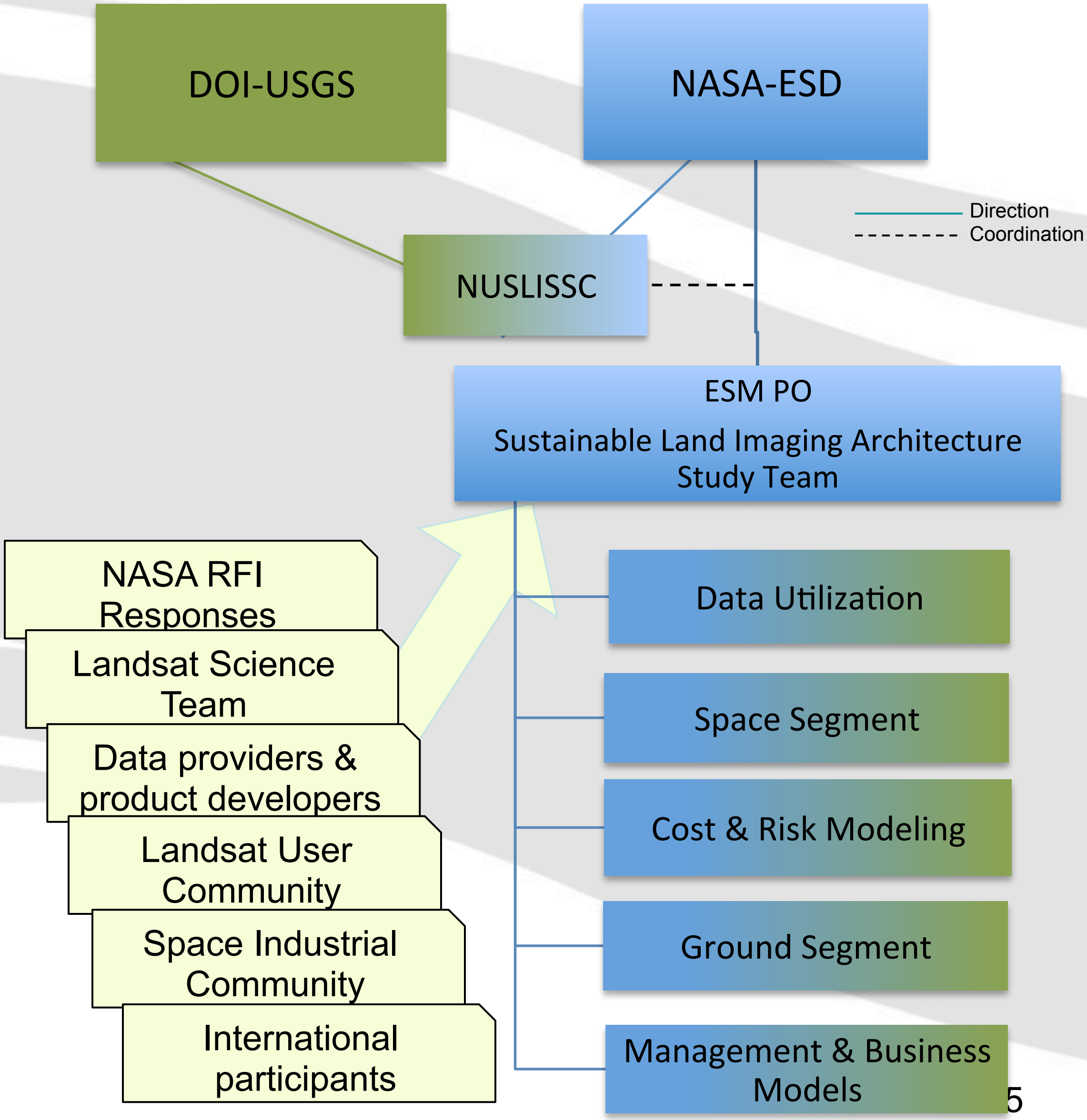
- **Sustainability**
  - The SLI program should provide the data products for the long haul, without extraordinary infusions of funds, within the budget guidance provided.
  - It should also ensure the technology required for the program is available and appropriate for the long haul

- **Continuity**
  - The SLI program should continue the long term Landsat data record. This does not necessarily mean the imagery per se, but the usable products that define the utility of the data record.
  - Understanding how the data are used is essential when considering potential architectures.

- **Reliability**
  - The SLI program should exhibit a form of functional redundancy. The data sets should be able to draw on equivalent or near equivalent deliverables from different sources to provide the data for the highest priority land imaging data products.
  - With these "near equivalent" data sources identified in advance, the loss of a single satellite or instrument on orbit should not cripple the program or significantly impact users, and the program will exhibit graceful degradation.

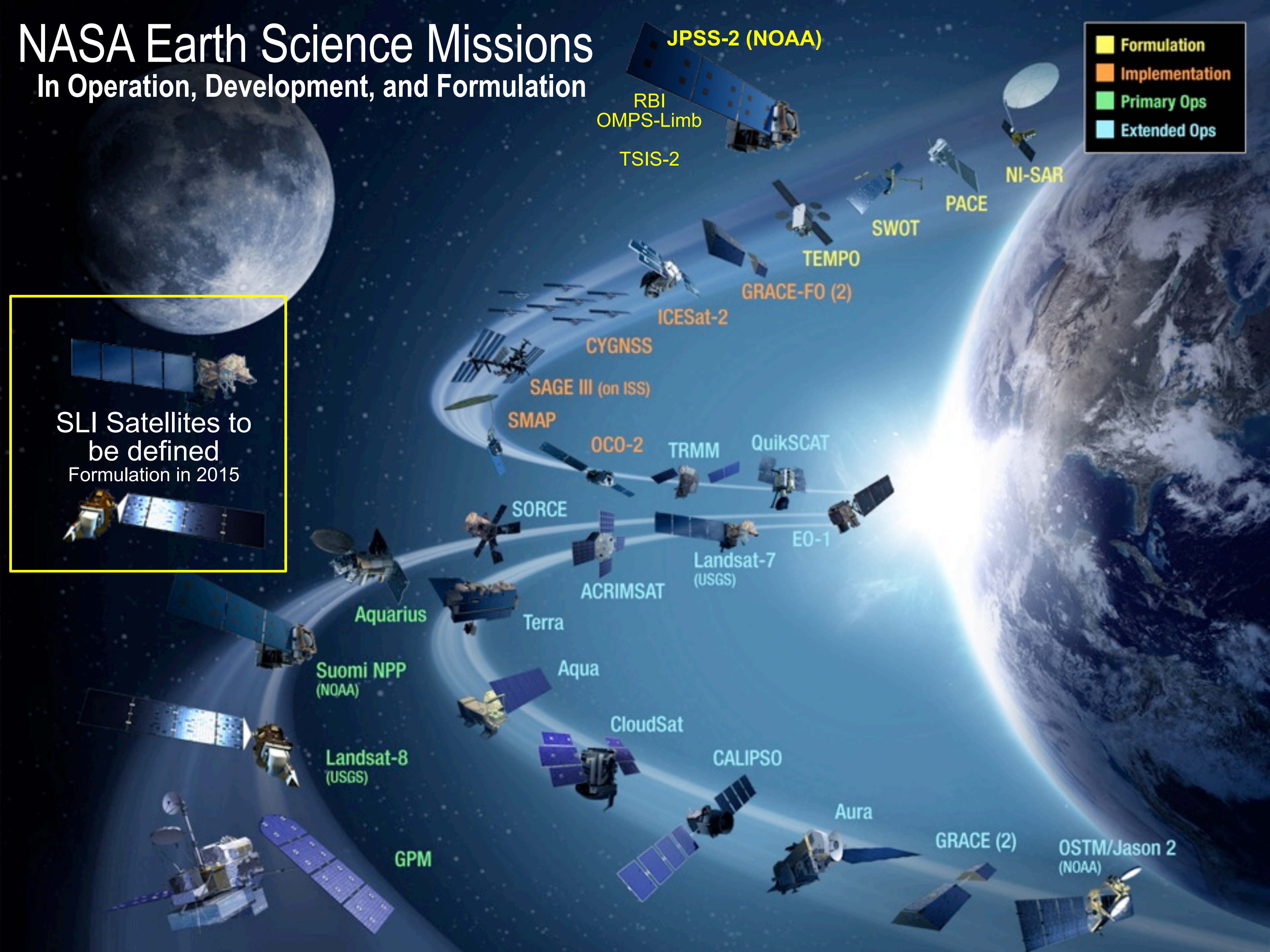
Sustainable Land Imaging Study Execution

- NASA leads the study, closely coordinated with USGS
- Multi-disciplinary Architecture Study Team (AST) executes the study for NASA
- AST is essentially governmental, including NASA, USGS, Aerospace, FFRDC
- We actively seek input from multiple sources and have taken multiple opportunities for community engagement
- The AST reports to the NASA ESD and NASA reports to the OSTP in August 2014



Established a Study Schedule in September

	FY13 Accomplishments	
	✦ Kick-off briefing to Administration	Aug 6, 2013
SLI Design Cycle #1	✦ Establish Architecture Study Team (AST)	Sept 2013
	✦ Industry & Partner Day, RFI Release	Sept 18, 2013
	✦ Landsat User's Forum	Dec 4, 2013
	FY14 Activities & Plans	
	✦ 1st Quarterly briefing to Stakeholders	Nov 21, 2013
	✦ 2nd Quarterly briefing to Stakeholders	Jan 27, 2014
SLI Design Cycle #2	✦ AST Design Cycle 2	Jan 27-Mar 15, 2014
	✦ 3rd Quarterly briefing to Stakeholders	Mar 18, 2014
	✦ **SLI Community/Industry Forum**	**Apr 1, 2014**
SLI Design Cycle #3	✦ NASA ESD SLI interim report to Congress	May 18, 2014
	✦ AST completion of full SLI program options	May 15-Jul 15, 2014
	✦ Completion of SLI study report	Jul 2014
	✦ NASA/USGS SLI report to Administration	Aug 15, 2014


NASA Earth Science Missions
In Operation, Development, and Formulation
JPSS-2 (NOAA)
RBI
OMPS-Limb
TSIS-2
Formulation
Implementation
Primary Ops
Extended Ops
NI-SAR
PACE
SWOT
TEMPO
GRACE-FO (2)
ICESat-2
CYGNSS
SAGE III (on ISS)
SMAP
OCO-2
TRMM
QuikSCAT
SORCE
EO-1
Landsat-7
(USGS)
ACRIMSAT
Terra
Aquarius
SLI Satellites to
be defined
Formulation in 2015
Suomi NPP
(NOAA)
Aqua
CloudSat
CALIPSO
Landsat-8
(USGS)
GPM
Aura
GRACE (2)
OSTM/Jason 2
(NOAA)

What are the SLI Study Deliverables?

- We have a 25 year program challenge to address, and we recognize the likelihood that the solution for the near term may be different, may evolve into a different form for the longer term
- Near-Term Solution
  - Will be defined at the outcome of this study activity in August 2014
  - Project and mission implementation activities, including procurement of mission elements, are expected in CY2014
- Mid- and Long-Term Solution(s)
  - We expect to identify possibilities for architecture options, but do not expect to know enough to firmly define them at this time
  - We need to understand what potential future capabilities and technologies may have, and what we can do now to better understand them
  - We plan to release study contracts in the coming months to inform these potential options

Questions

- Please step up to the microphone, and speak clearly into it with questions
- Please state your name and affiliation, then your question
- Questions from those watching online can be submitted to the following e-mail address:

HQ-LandImaging-RFI@mail.nasa.gov

- For questions submitted via e-mail, please include your name and affiliation

Sustained Land Imaging Architecture Study Interim Status Briefing

NASA Headquarters

April 1, 2014

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Del Jenstrom – AST Manager

1. INTRODUCTION AND OVERVIEW

Land Imaging AST Charge, Process, & Membership

Land Imaging AST Charge (September 2013)

- Define a Sustainable Land Imaging (SLI) system delivering global land-imaging multispectral and thermal infrared information for a 20-year period starting in 2018
- Provide options which consider various weightings of near-term capability, continuity/ gap risk mitigation, technology infusion over the system's lifetime, and cost
- Consider refined capabilities requested by the user communities
- Include consideration of new measurement approaches, as well as potential international and private sector partnerships

AST Study Process

- Establish study trade space via expert knowledge, intensive AST discussions, and RFI responses
- Trade space is explored via several design cycles, and adjusted through each
- Appealing architectures that are likely to satisfy budget constraints are further refined and assessed

AST Membership

- Representatives from NASA/GSFC, NASA/LaRC, NASA/ARC, JPL, USGS, JHU/APL, Aerospace, and MIT/LL

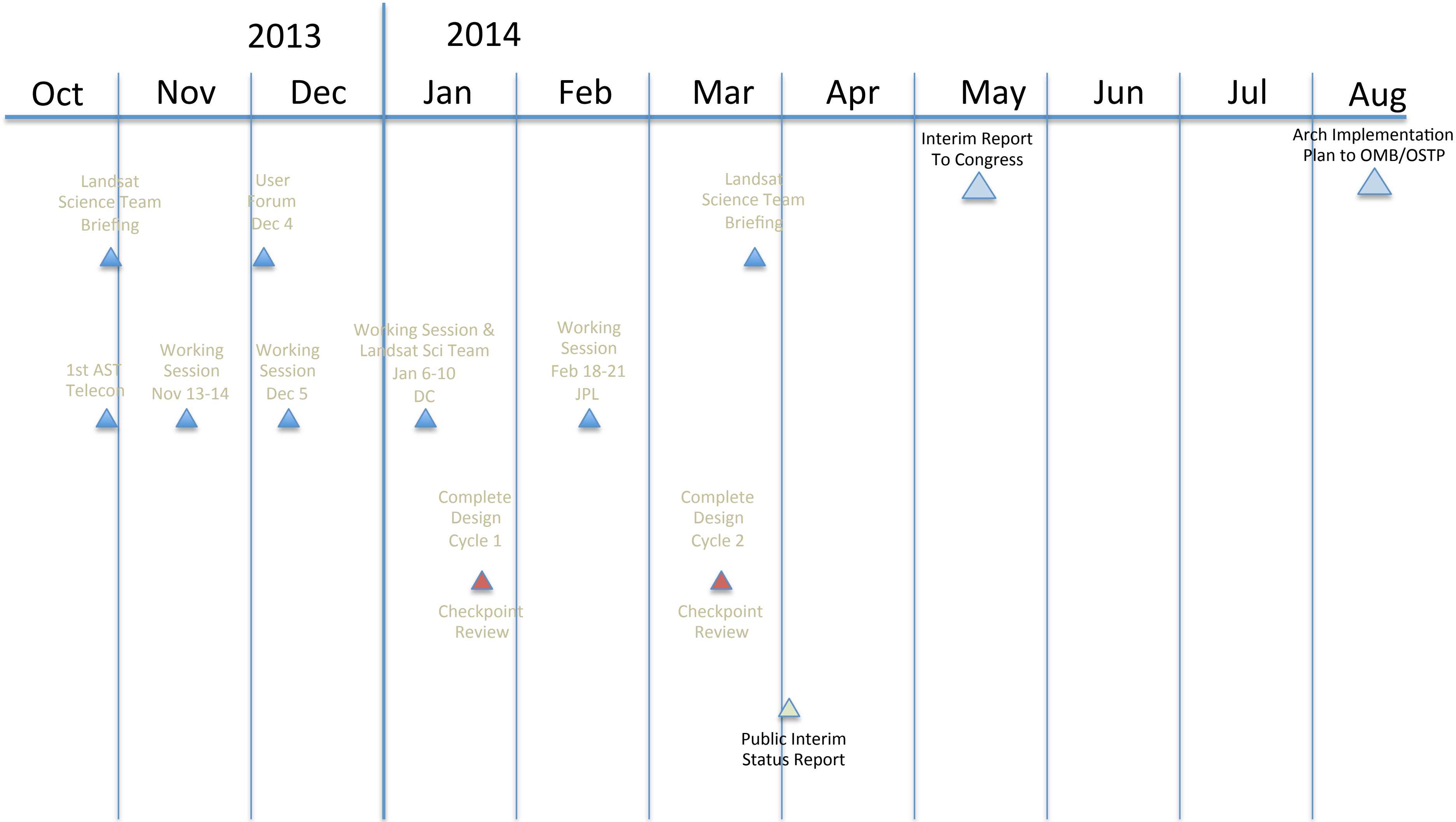
NASA Land Imaging Budget

- The President's FY 2014 Budget Submittal for NASA's Sustained Land Imaging activities, released in April 2013

$K	FY 14	FY 15	FY 16	FY 17	FY 18	FY 19
Land Imaging	30,000	84,000	94,800	117,900	117,900	-

- Per ESD direction assume for planning purposes: $120M in FY19 as the base year and inflation adjust in FY20 and beyond

AST Study Timeline & Milestones



AST Status (1 of 2)

- Architecture class structure established spanning the trade space
- AST has established representative instrument/mission/architecture concepts for all architecture classes under consideration and mapped those to various business models
  - RFI responses were again reviewed to ensure concepts adequately included in analyses
- Cost model building blocks have been established for each technical and programmatic permutation
  - Representative instrument/spacecraft concepts developed
- AST has iterated architecture value metrics with ESD and devised a three-phase approach
  - Phase I: Availability assessments relative to historical Landsat record
  - Phase II: Programmatic and technical factors
  - Phase III: More detailed analyses of very limited set of options

AST Status (2 of 2)

- AST has completed Phase I value metric assessments for large trade space of architecture permutations
  - Sufficient to draw some meaningful conclusions
- Phase II assessment is currently underway
  - Refining Phase II value metrics
- Phase III down-select and analysis will occur in April/May
- AST is still open to new ideas not yet considered!
  - Now that process/recipe established, new ideas can be compared quickly
- AST actively assessing advanced techniques and technologies to reduce cost and improve performance
  - Evaluating smaller instruments and spacecraft technologies relative to satisfying Landsat data quality requirements
  - Evaluating hyperspectral benefits and risks
    - Assessing hyperspectral aircraft data relative to Landsat 8 data
    - Assessing technical risks for future space implementation

AST Observations (1 of 2)

- The future Sustainable Land Imaging program must continue to provide the ***backbone*** capability historically played by Landsat
  - There is currently no comparable program to Landsat: it is the reference standard for land imaging relied on by other programs
    - Sentinel 2 may become similarly capable in reflective bands, but is yet unproven
  - Landsat sets the standard for data usability; this must continue
  - Data must be ~co-temporal, coregistered, calibrated & full-spectrum: VIS-NIR-SWIR-TIR
  - Data must have routine global & synoptic coverage
  - Data needs to be acquired from a sun-synchronous vantage point
  - Land Imaging should strive to only employ mature technologies operationally
    - Demonstration of promising new technology should be done "off line"
  - Science and operational users expect and require stability
    - New approaches must enable continuation of historical record

AST Observations (2 of 2)

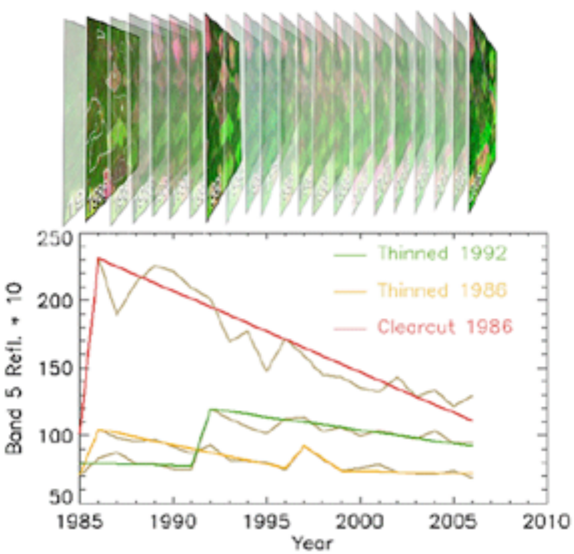
- BOL performance of Landsat 8 is excellent
  - Some aspects of OLI performance (e.g. SNR) may exceed the needs of many users
  - Landsat-8 (including TIRS) is likely to continue well beyond its design life
    - Possibility of random failure increases slowly but monotonically
- For a significant portion of Landsat history the repeat time has been 8 days, hence this most closely represents "continuity" to the user community
- A launch failure may occur, a random failure on orbit may occur
  - The system must be robust to a single failure
- The SLI program budget profile is the dominant driver of the architecture trade space
- AST has identified viable architectures within the constraints of the study
  - However, those approaches that satisfy the value metrics have their own unique drawbacks and risks
- AST results will guide initial SLI Program direction
  - Determine feasibility of sufficiently satisfying user needs within sustainable program
  - Identify promising architectures
  - Enable near-term decisions for initial program direction and investments
  - Ongoing studies and technology investments by the SLI program will be required to refine the program plan

Jeff Masek

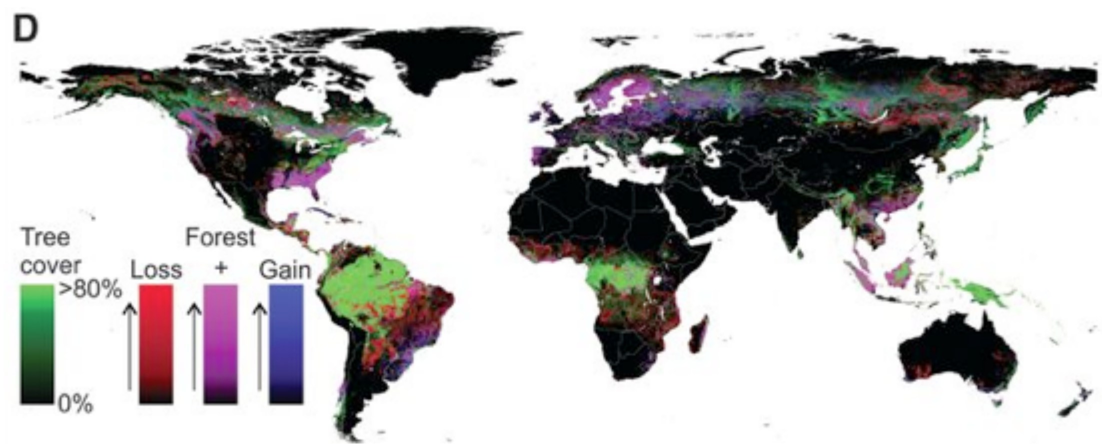
2. SCIENCE INTRODUCTION

Land Imaging Continuity

- 41-year Landsat record of land cover, land use, and vegetation condition
- Landsat remains the most cited land remote sensing system in the peer-reviewed scientific literature
- Opening of free USGS archive in 2008 has ushered in new era of applications:
- New focus on leveraging **time domain**
    - *Inter-annual disturbance, compositional change, land use*
    - *Intra-annual phenology, vegetation condition, compositing*
- **Large area** coverage for continental land cover studies



R. Kennedy, LandTrender disturbance algorithm

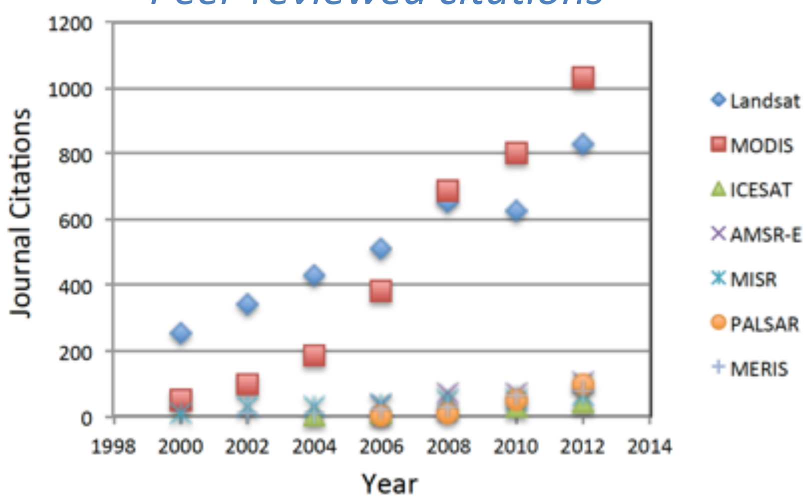


Hansen et al., Science 2013

What Makes Landsat Heritage Unique?

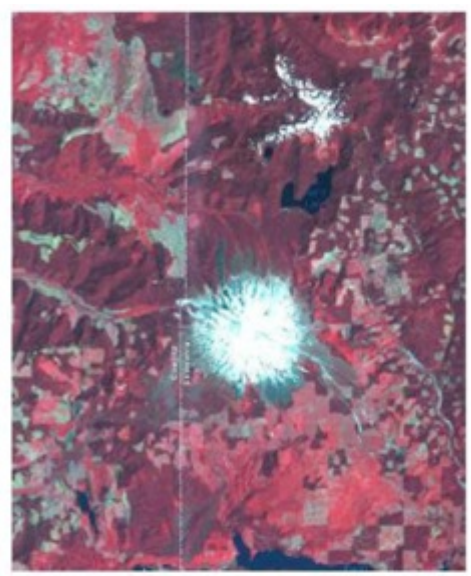
- Global acquisition policy
- Free, open, distribution & easy access
- Calibrated, science-quality data covering full VNIR-SWIR-TIR
- Resolution sufficient to separate natural & anthropogenic land change
- Continuous 42-year archive

Peer-reviewed citations

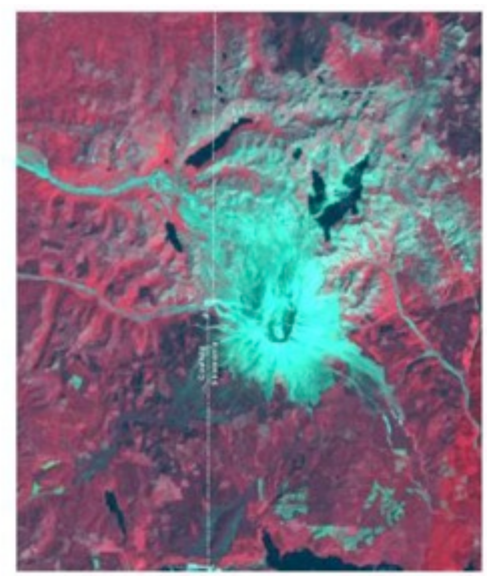


From ISI Web of Science Science Citation Index Expanded. Does not include Conference Proceedings

Mt St. Helens 1975-2005



Landsat MSS imagery 1975

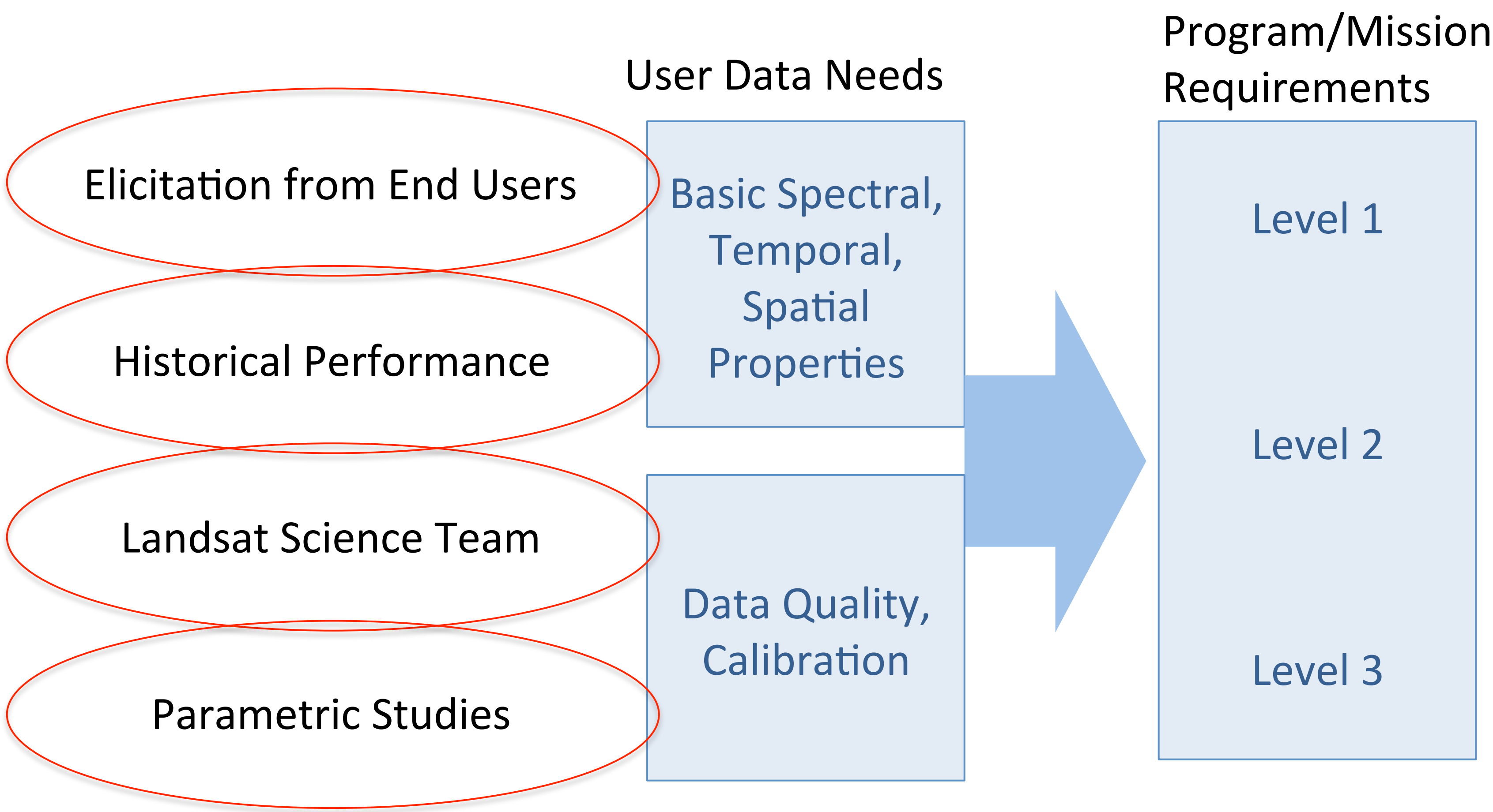


Landsat 7 imagery 2005

Jim Nelson

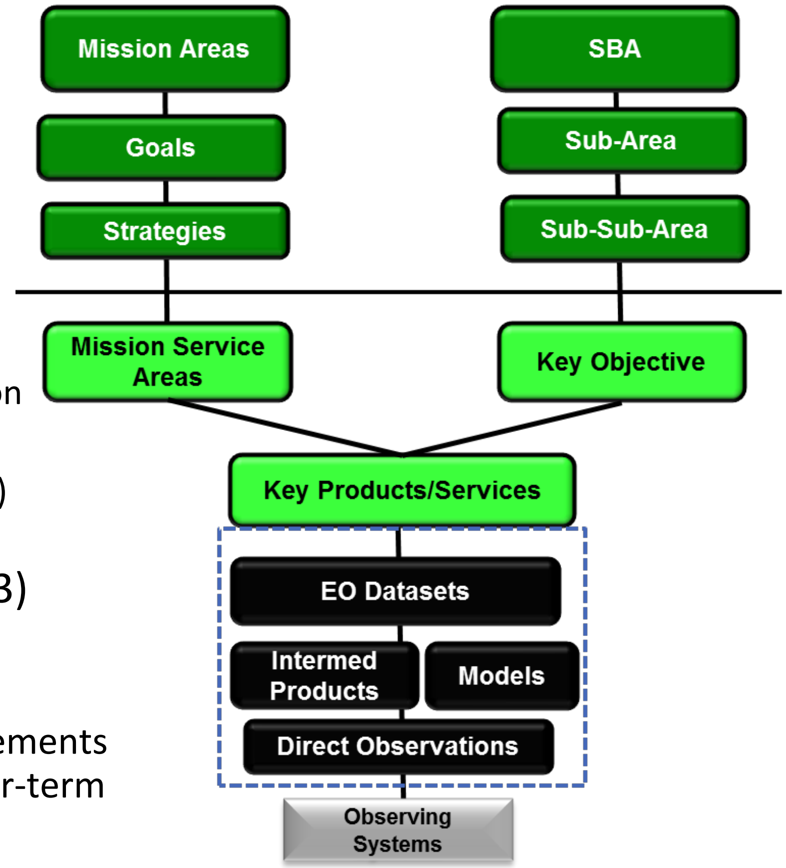
3. USGS USER NEEDS ASSESSMENT

Framework for AST User Needs Assessment



USGS National Land Imaging Requirements Project

- President's FY12 budget request include language for the USGS for "understanding Federal land imaging requirements"
  - Initiated National Land Imaging Requirements Project
- Two components:
  - **<u>User Requirements Elicitation</u>**
    - All US land imaging needs
    - Repeatable and transparent process
    - Traceability of requirements via value tree
  - **<u>System Development</u>**: Earth Observation Requirements Evaluation System (EORES)
    - Repository for requirements & capabilities information
    - Analytical tools
    - Joint development with NOAA (Atmosphere & Ocean)
- NLIR Moderate Resolution Pilot Project (Jun-Dec 2013)
  - Purpose was to test the requirements elicitation methodology, process, and tools
  - Provided representative sample of applications/requirements which use moderate resolution imagery to support near-term mission-formulation efforts
  - Focus on applications using moderate resolution imagery (5-120 m resolution)

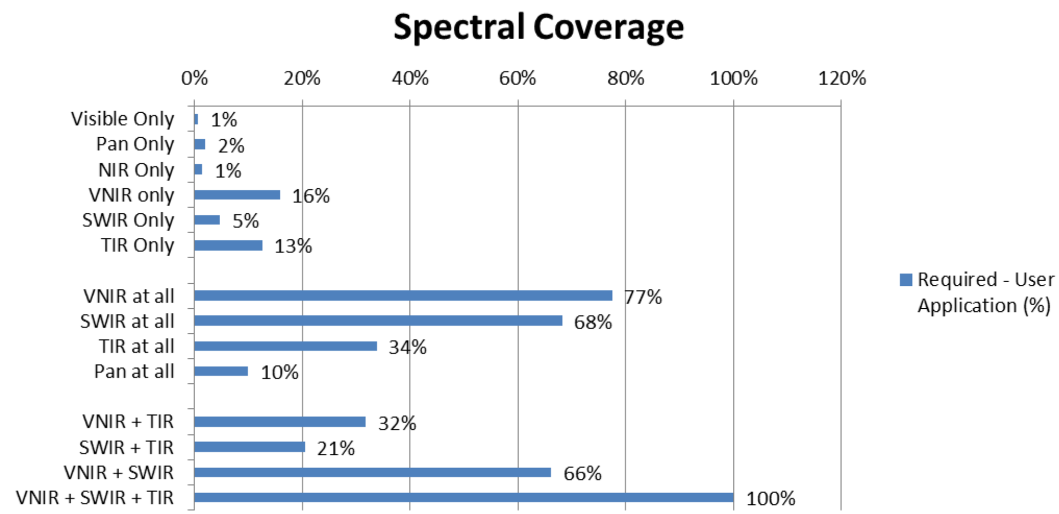


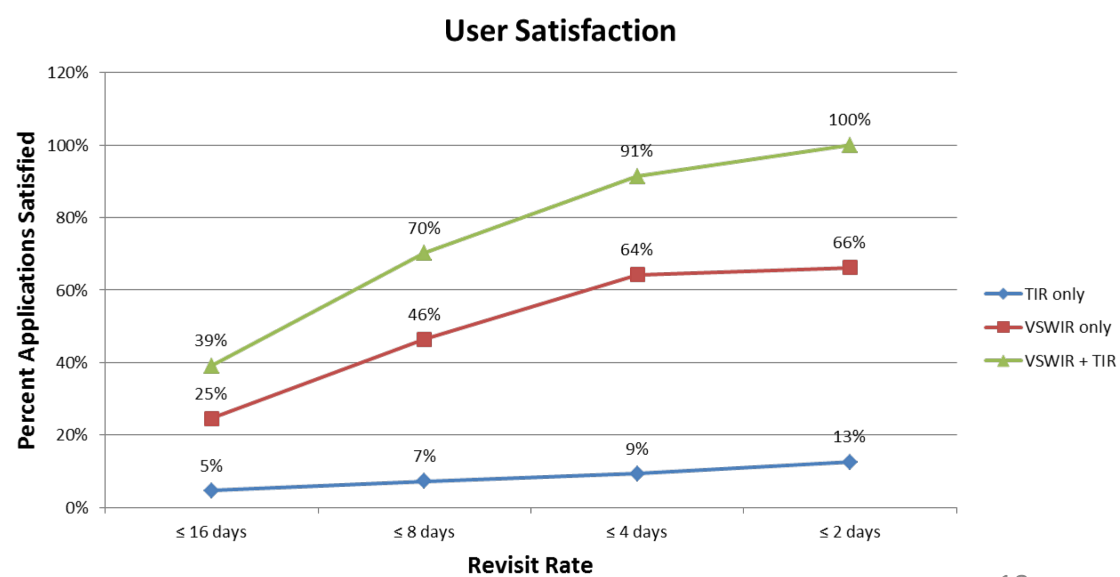
Characterization of End User Needs

- Land Imaging user needs derived from targeted elicitations of Land Imaging user community
  - National Land Imaging Requirements (NLIR) moderate resolution pilot project
  - Landsat Applications Requirements assessment for the 2012 USGS RFI
  - Landsat Science Team application assessment
  - Resulted in 151 distinct, representative user applications where Landsat data are used routinely to produce and provide consistent services or informational products
- Government and university application sources elicited include:
  - *Bureau of Indian Affairs*
  - *Bureau of Land Management*
  - *Bureau of Reclamation*
  - *Fish and Wildlife Service*
  - *National Park Service*
  - *Office of Surface Mining*
  - *State Government (Ohio & Western States Evapotranspiration)*
  - *Universities (Idaho, Maryland)*
  - *U.S. Department of Agriculture (ARS, FAS, FS, FSA, NASS, NRCS, RMA)*
  - *USGS*
  - *NASA*
- Six of the nine NEO Societal Benefit Areas (SBA's) are addressed – These include:
  - (1) Agriculture & Forestry, (2) Climate, (3) Disasters, (4) Ecosystems, (5) Energy & Mineral Resources, and (6) Water Resources
- Note: Comparative importance of user applications not assessed

Land Imaging User Needs Statistics

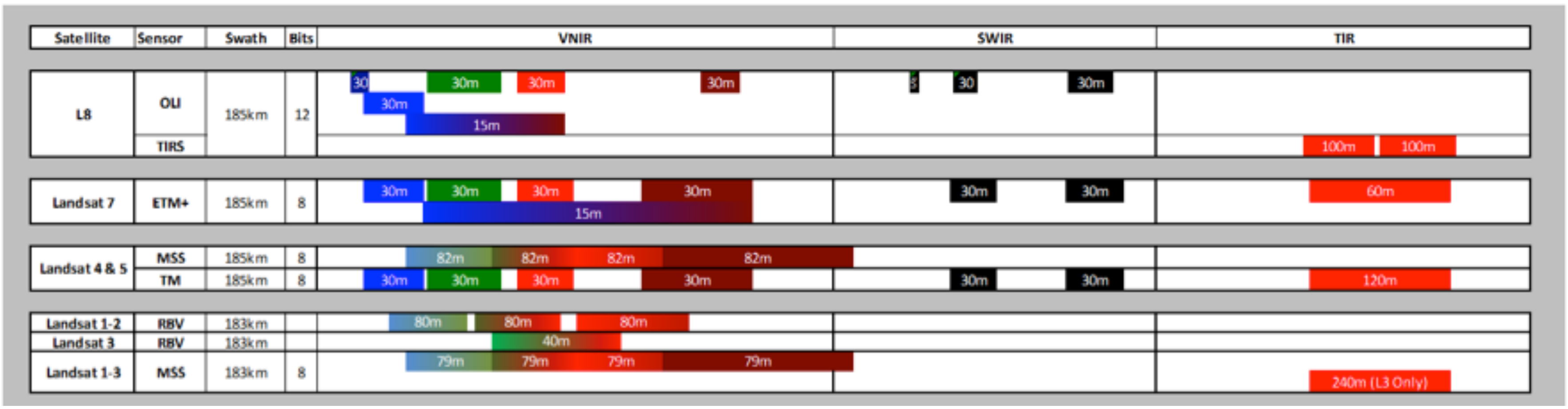
- Spatial resolution
  - Majority of routine user applications require 30m for VSWIR, 120m for TIR
- Spectral Coverage
  - User applications clearly rely heavily on aggregated band combinations
  - Very few visible spectra only (or VNIR only) applications were identified
  - Simultaneous VSWIR and TIR measurement provide significantly more value than each measurement individually
- Revisit Rate
  - User need for increased revisit rates clearly evident with 70% of applications requiring ≤ 8 day revisit
  - Revisit rate of 16 days satisfies less than 40% of user applications



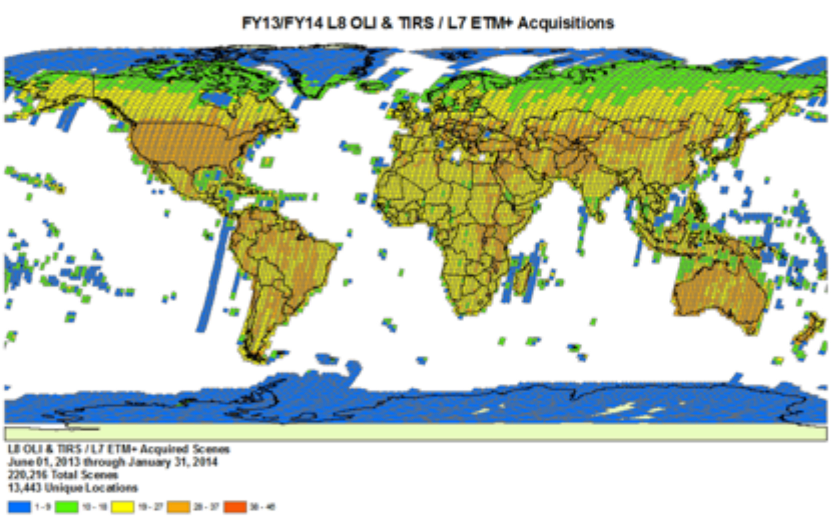


Historical Landsat Capabilities

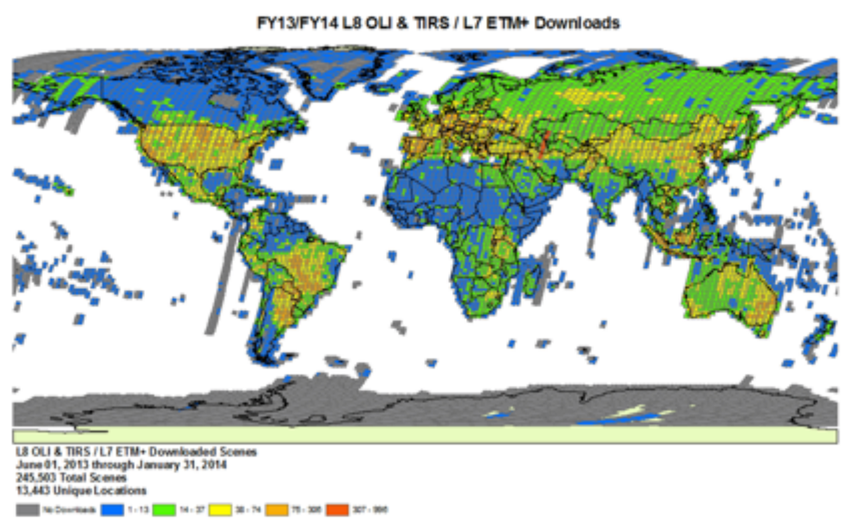
Full Spectrum Coverage



Global Acquisition

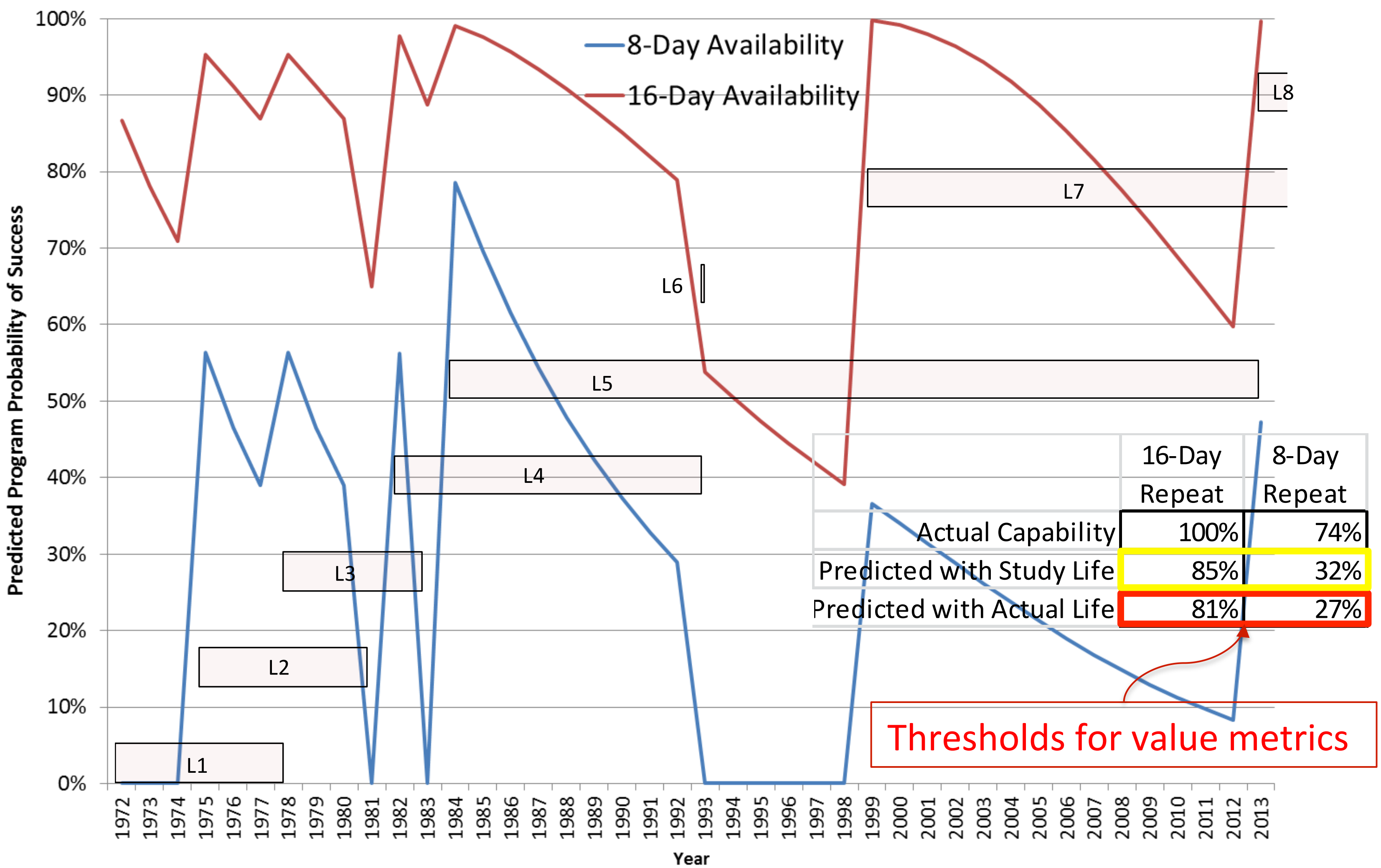


Global Distribution



Historical Availability – Calculated Reliability

Calculated Program Probability of Success - Predicted with Actual Life



	16-Day Repeat	8-Day Repeat
Actual Capability	100%	74%
Predicted with Study Life	85%	32%
Predicted with Actual Life	81%	27%

User Needs to Value Metrics

- Land Imaging user needs cover needs of the US Land Imaging community
  - Landsat provides the foundation for a US land imaging capability and provides the most critical subset of capabilities required to meet the needs of the user community (70% of user applications surveyed)
    - Systematic global coverage, 8 day revisit rate (16 day per satellite) of well-calibrated VNIR/SWIR/TIR coverage
  - Some users require capabilities beyond what Landsat has traditionally provided (e.g., higher revisit rate, smaller GSD, more spectral coverage)
    - Users to date have either purchased data to augment Landsat, proceeded with a reduced capability with reduced utility, or developed alternative methods for their applications

- AST Value Metrics are based on historical availability (Landsat continuity) rather than Land Imaging User Needs (NLIR) data
  - Full spectrum, global acquisition and distribution (required of all architectures)
  - Historical availability of 8-day (baseline) and 16-day (threshold) revisit rate

Jeff Masek

4. IMAGING PERFORMANCE CHARACTERISTICS

LST Definition of Continuity

The USGS-NASA Landsat Science Team defines Landsat data continuity as the collection, archival, and distribution of image data of the Earth's continents and surrounding coastal regions with the content, quality and coverage needed to map, monitor and assess the Earth's characteristics and its response to natural and human-induced change. To accomplish this, continuity includes:

- Long-term calibrated measurements that are consistent across the changing instrument record.
- A continuous record since the initiation of observations with no significant temporal or geographic data gaps.
- Measurements that enable backward and forward assessments of the conditions and changes in the Earth's surface.
- Measurements with comparable spectral, spatial, temporal, and geographic properties that result in sufficiently consistent and accurate documentation of surface characteristic and dynamics.

See "USGS-NASA Landsat Science Team Statement of Landsat Continuity: Priorities for a Future Land Imaging Architecture for Sustained Landsat Observations" (January 23, 2014)

Key Performance Aspects

Performance	Rationale
Spectral coverage across VNIR, SWIR, and Thermal IR (TIR)	• *Most applications require multiple spectral regions (68% of NLIR applications require SWIR; 34% require TIR)*
30m VSWIR spatial resolution 120m TIR spatial resolution (60 m preferred)	• *Spatial resolution supports land management, land use, and ecosystem studies;* • *Broad area coverage supports regional/continental monitoring*
Ability to image each point on the globe every 16 days (8 days preferred)	• *Time series needed to characterize seasonal change* • *More frequent observations help mitigate cloud cover*
Sun-synchronous orbit, 10 AM crossing time (+/- 30min)	• *Radiometric consistency for interannual mapping of change; continuity with existing Landsat record*
Near co-incident imaging of spectral bands (VSWIR within seconds; TIR within minutes of VSWIR)	• *Near-simultaneous VSWIR required for multi-band indices;* • *TIR and VSWIR coincidence supports ET, water resources applications*
Global coverage of land area	• *Required for global land science & applications*
Less than 5% uncertainty in absolute spectral radiance	• *Provides radiometric continuity for long-term monitoring and change detection*
View angles < +/- 15 degrees	• *Limit BRDF variability within archive*
Free and open data distribution	• *Hallmark of Landsat program*

See "USGS-NASA Landsat Science Team Statement of Landsat Continuity: Priorities for a Future Land Imaging Architecture for Sustained Landsat Observations" (January 23, 2014)

Driving Parameters: Why are they Critical?

- Sun-synchronous orbit
- View Angle < +/- 15 degrees
- VSWIR & TIR band simultaneity
- Band co-registration
- Radiometric calibration, uniformity, stability

Orbit Geometry

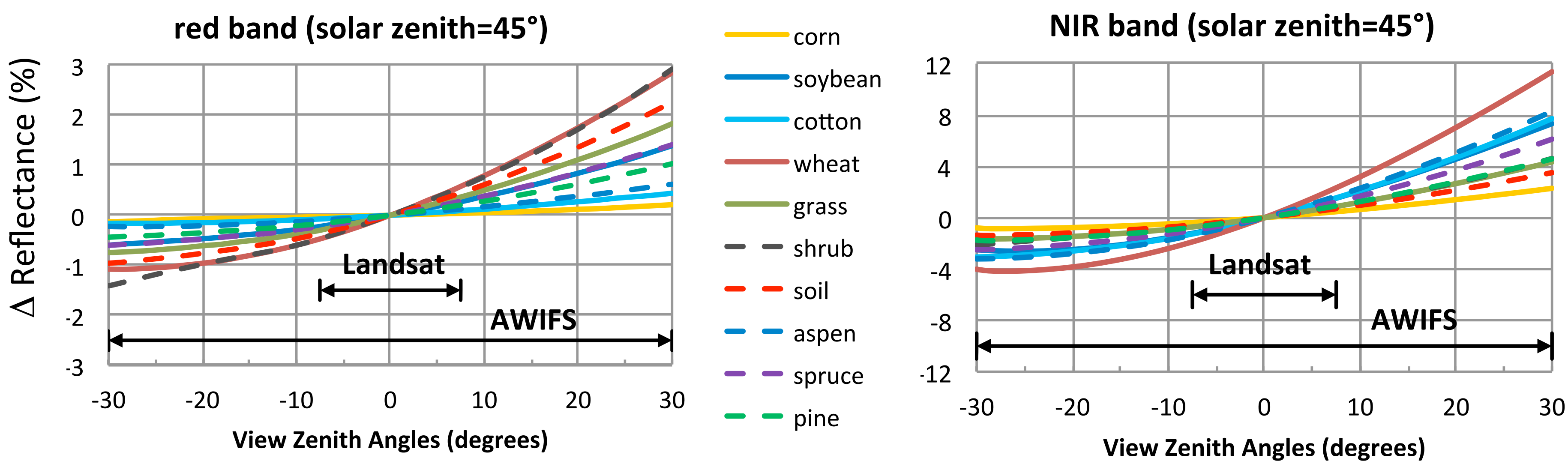
- Sun-synchronous geometry critical for VSWIR bands
  - Required for consistent illumination for inter-annual change detection
  - Common requirement among all national and commercial moderate-resolution optical systems (MODIS, VIIRS, Sentinel-2, DMC, etc…)
  - Mid-morning to be compatible with the Landsat archive

- Also desirable for TIR / Evapotranspiration (ET) applications
  - Same time of day useful for consistent thermal state
  - Morning observations desirable for cloud cover, energy balance models

- Eliminates low inclination orbits, including ISS as operational platform
  - Low inclination orbits for TIR remain interesting for particular research purposes

View Geometry

- Directional reflectance changes substantially with view angle (BRDF), with variations becoming acute for > ~ +/- 20 degrees
- Mixing a range of FOV's can add "noise" to spectral time series
- Landsat ST has recommended restricting view angle to < +/- 15 degrees (current Landsat is +/- 7.5 degrees)
- Wider swath width suggested by NAS Study "Landsat and Beyond"



Gao et al., 2014, Angular Effects and Correction for Medium Resolution Sensors to Support Crop Monitoring, in press JSTARS

Band Simultaneity

- VSWIR bands should be collected within a few seconds
  - Multi-band indices need to "see" the same atmosphere for accuracy
- Simultaneity between TIR & VSWIR depends on application
  - Cloud screening requires all bands within *seconds*
    - VSWIR-only cloud algorithms exist
    - But… "smearing" of clouds from non-simultaneous acquisition decreases usable data within each image
  - Hydrodynamics (water resources) requires bands within *minutes*
  - Evapotranspiration requires data within *hours* or longer
  - Landsat Science Team prefers TIR and VSWIR data acquired at once (ie. within seconds)
- Current AST architectures assumed:
  - TIR & VSWIR collection within one minute

Band-to-Band Registration

- Misregistration of less than 0.20 pixels typically required for accurate (<10% error) multi-band indices & change detection (*Townshend et al., 1992, IEEE Trans. Geosci. and Remote Sens.*)

- Current L8 Spec is:
  - 4.5m (LE90) or 0.15 VSWIR pixel within VSWIR bands
  - 30m (LE90) or 0.25 TIR pixel between TIR and VSWIR
  - Relaxed relative to L7 performance of ~0.08 pixel within VSWIR

- Admits disaggregated architectures, but…
  - Requires tight pointing knowledge and/or ground processing to register bands
  - Requires VSWIR registration band for TIR free-flyer

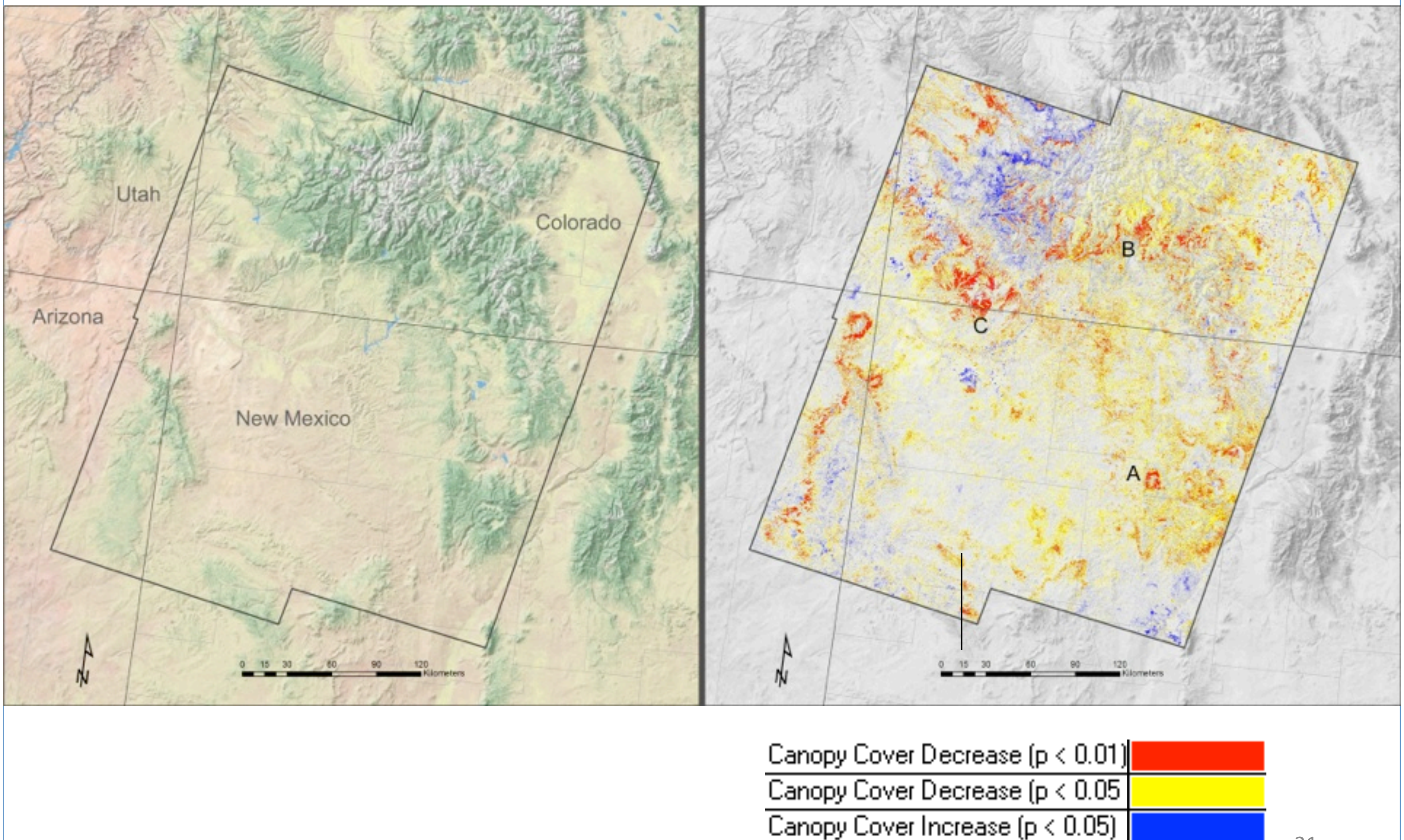
- Combined, the B2B registration and band simultaneity requirements drive implementations to not disaggregate reflective bands between separate spacecraft

Radiometric Characteristics

Radiometry should be:

- **Stable** – Allows trends in land condition to be tracked within seasons (e.g. crop phenology) and across decades (e.g. climate impacts, ecologic change)
  - Short term radiometric stability is probably a greater design driver than absolute accuracy: 0.5% over 60 sec; 1% over 16 days; 2% over 5 years
- **Uniform** – Allows consistent, automated mapping of land cover across broad areas. Requires:
  - Tight control of spectral bandpass across FOV's
    - Telecentric optics (and/or compensation) & careful selection of filters
  - Instrument thermal control
- **Calibrated** to radiance, reflectance – Critical for long-term science applications of the data set
  - Integration with other data sets (e.g. MODIS, VIIRS, international sensors)
  - Retrieval of physical parameters (temperature, vegetation indices)
  - Fundamental reference for consistent, long-term archive

Gradual Canopy Change in Four-Corners Region of US Southwest



Long-term Calibration Required to Measure Long-term Changes

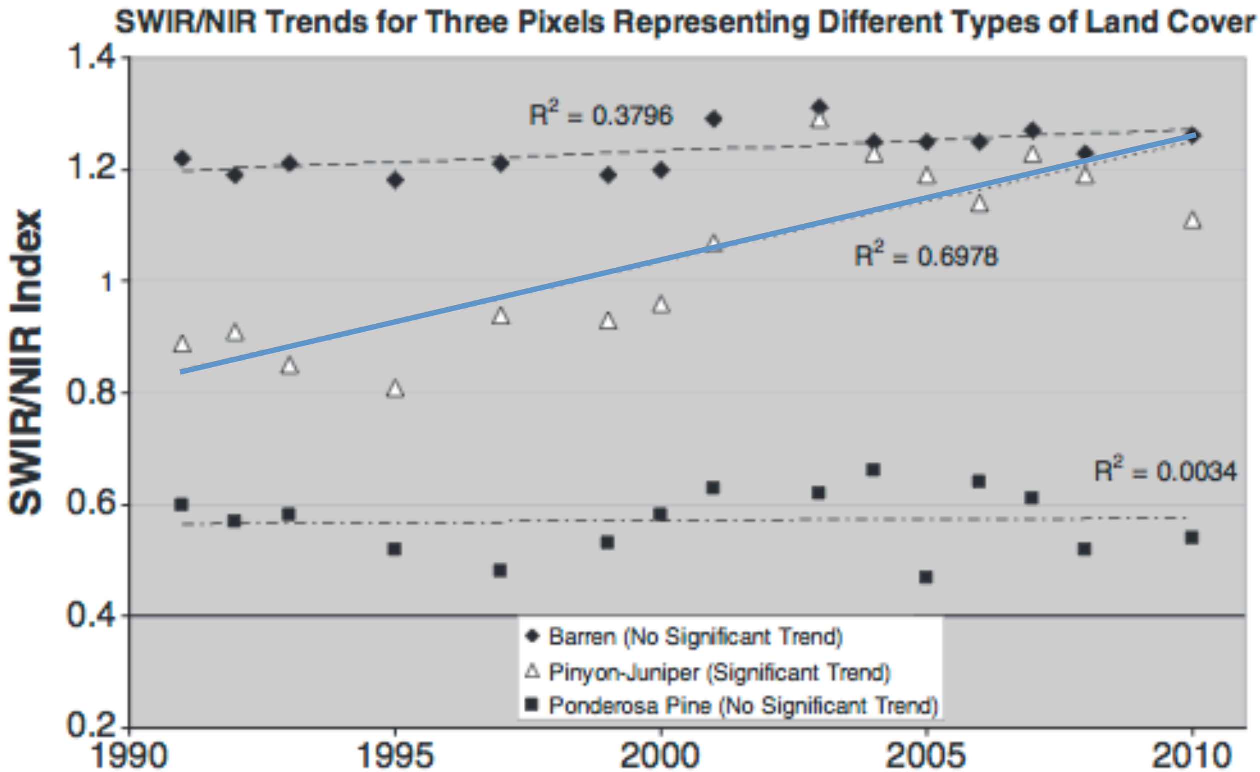


Fig. 2. Example of SWIR/NIR regression model trends for selected individual pixels representing different land cover types and conditions. This example is from the southwestern US study area.

Vogelmann et al., Monitoring gradual ecosystem change using Landsat time series analysis: case studies in selected forest and rangeland ecosystems , Remote Sens. Environ, 2012

On-board Calibration

- Provision of on-board calibration (e.g. solar diffuser) provides several important capabilities:
  - Ability to flat-field detectors (ie. characterize Per-Pixel Uniformity)
  - Tie to absolute reflectance standard via lab-measured diffuser
  - Ability to assess stability as often as needed (not just once-per-cycle)
    - Essential for both VSWIR and TIR
    - SWIR and TIR particularly sensitive to baseline (bias) drift
- It may be possible to obtain some of these capabilities without on-board calibration using vicarious or PICS (Pseudo-invariant Calibration Sites)
  - Flat-fielding via side slither or global averages
  - Stability at ~monthly time scales using PICS (but need stable instrument over shorter intervals)
  - Absolute calibration via vicarious campaigns or sensor cross-calibration (but which sensors?)
- The Landsat Calibration Team will report back within a year on the efficacy of relying on PICS approaches for absolute calibration
  - For now, all AST instrument concepts nominally include a single solar diffuser and stimulation lamps
  - Landsat has historically been the backbone for cross-calibrating the global moderate-resolution constellation
- Removing on-board hardware increases the need for inherent radiometric stability and uniformity, which remain instrument design drivers.
  - Difficult to evaluate instrument stability pre-launch

Parametric Studies

- AST and the Landsat Science Team are using parametric studies to refine established land imaging requirements
  - Are there driving requirements that could be relaxed?
  - What is the science and applications impact of relaxing requirements?

- Ongoing studies
  - What VSWIR SNR is required for land cover classification, biophysical retrievals?
    - Improved SNR was #1 priority of Landsat-7 Science Team circa-2000 due to saturation of TM & ETM+ data over snow, deserts, and poor radiometric resolution for dark targets
    - OLI SNR surpasses current requirements by 2-3X
    - LST degraded OLI data to obtain ETM+- & OLI-required SNR
    - OLI *required* SNR shows substantial benefits; OLI SNR *performance* less critical
  - What image acquisition frequency is required for seasonal, cloud-free views?
    - MODIS cloud cover data used to model probability of obtaining clear view
    - 8-day coverage required to obtain clear view over Eastern US with >80% Ps
  - VSWIR vs. TIR time separation for ET modeling
  - OLI aliasing requirements
  - Spectral uniformity, stray light

Phil Dabney

5. REPRESENTATIVE INSTRUMENT CONCEPTS

Near-Term Satellites Under Consideration

- Requirements driven
  - Full spectral coverage VNIR, SWIR, TIR
  - 30m (120m) spatial resolution VSWIR (TIR)
  - Threshold 16 day coverage; Historical baseline 8 day coverage
  - Global land coverage
- Existing / proven technology for near-term implementation
  - L8 clone
  - New design built to L8 requirements
  - TIR only gap filler
- Launch availability & cost
  - New launch options affect trade space

Instrument Point Designs

- The AST investigated near-term full-capability point designs to span the trade space with high fidelity well understood data points
  - Enough detail exists or was obtained to provide credible costing and system level impacts on space craft and launch vehicles.
  - These ranged across traditional L-8 clones, modified "clones", to newer smaller designs

- These point designs were developed, drawing on information from
  - RFI responses
  - L-8 government instrument team
  - Past land imager and mission design studies funded by NASA
  - AST directed studies held at both GSFC and JPL using their instrument design labs

- Representative instrument concepts were established to span a broad parametric trade space
  - AST has high confidence that concepts will satisfy Landsat-quality image requirements

Instrument Point Designs – cont.

- The designs span a large parameter space
  - Total mass with the current OLI+TIRS at 650 kg down to the small full-spectrum payload at 150kg
  - Volumes ranging from to 7 m^3 down to 0.7 m^3
  - Swath width of 15 degrees (16-day repeat) to 30 degrees (8-day repeat)

- Instrument concepts used in architecture modeling studies
  - Landsat 8 Clone instruments
    - OLI Clone
    - TIRS Clone
  - Smaller VSWIR instrument
    - A smaller reflective band pushbroom imager similar to EO-1/ALI using well established detector technologies
  - Smaller TIR instrument
    - A smaller thermal imager representative of several known concepts
  - Small full-spectrum 15 deg. swath payload (VSWIR + TIR)
    - AST concept was a single scanning instrument
    - Could be scanner, pushbroom, or multiple refractor
  - Small full-spectrum 30 deg. swath payload (VSWIR + TIR)
    - AST concept was a single scanning instrument
    - Could be scanner, pushbroom, or multiple refractor

Longer-Term Satellites Under Consideration

- Potential future directions
  - Smaller satellites and imagers
    - Mini-Sats (100-200kg) have most mid-term promise
      - The ESPA ring class assume rides to 10 AM polar orbit are available
    - Micro-/nano-/cubesats require additional technology development
  - Hyperspectral
    - Could provide additional science for future Land Imaging
- AST investigations
  - Explored technical challenges of smaller satellite concepts outlined in RFIs
  - AST instrument design sessions
    - JPL Architecture Team session on range of small-sats to cubesats
    - Ongoing analysis of possible solutions
  - Exploring hyperspectral implementation
    - Simulating Landsat VSWIR data based on AVIRIS to compare with Landsat 8 OLI
    - Investigation of hyperspectral instrument risks and advantages
- Technology roadmap
  - Addressing specific technologies and directions for investment
  - Assumes some level of technology infusion from SLI program

Smaller Satellite Feasibility and Maturity

- The AST examined existing and recently launched nano/micro/mini-sats:
  - Determined and/or estimated capabilities and technologies used based on a variety of sources
  - Estimated limitations to performance based on physics and technology
    - A physics first principles approach to spatial resolution based on dimensional constraints
    - Limitations on wavelength coverage due to detectors
    - Considered limitations on fields-of-view in telescope designs
  - Limitations to observatory orbit maintenance and pointing capabilities

- AST participated in a JPL A-Team study on Cubesat imager capabilities and technical challenges
  - Results from initial study report are still being analyzed and refined

- Initial conclusions:
  - Current state of nano-sats/cubesats (1-10 kg) do not yield sufficient capability to replace Landsat
  - Micro-sats (10-100 kg) have potential to meet portions of the Landsat mission with technology development
  - Mini-sats (100-200 kg) may currently meet some of the Landsat mission requirements
    - Questions remain about on-board calibration
  - U.S Government investment in capability may yield beneficial results for Land Imaging applications
    - Enhance potential for VNIR & SWIR augmentation
    - Enhanced propulsion and stability control

Compact Imager Ongoing Feasibility Assessment

- The AST continues to investigate the physical limits to shrinking imagers to fit in nano-sats (e.g. cubesats) and micro-sats form factors
  - Telescopes are considered the top limiting factor
    - Studied ways to shrink the known "fully capable" designs
    - The smallest 15 deg FOV telescope that works well in the VSWIR spectral range takes up at least 12U of space for the telescope
    - Investigating approaches to provide an effective 15 deg FOV with multiple spacecraft
  - Focal plane requirements that enable these smaller telescopes are being identified
    - Some candidate models have been identified
    - Performance impacts on shrinking the focal planes have been identified
    - Curved FPAs are being investigated
    - Tech gaps are being cataloged for future technology investment

Tony Freeman

6. ARCHITECTURE ASSESSMENT PROCESS

Process Overview

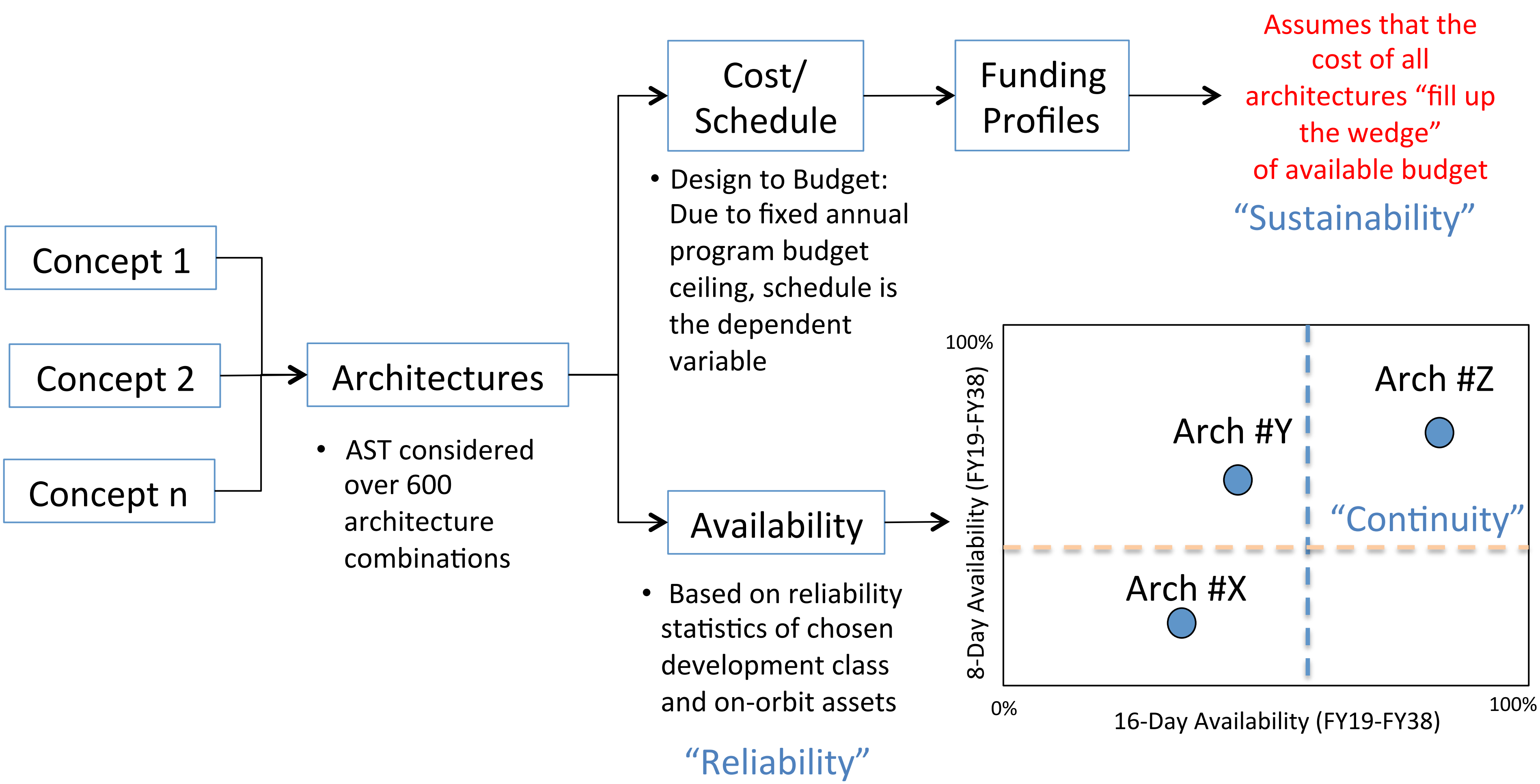
- AST has attempted to map the prime study tenets of Sustainability, Continuity, and Reliability into our metrics and assessment process
- Satisfaction of user community needs is reflected by comparison to historical Landsat capabilities
  - Secondary metrics are being assessed to address the degree to which architectures satisfy other user desires
- AST process has evolved into a phased sequence to enable first phase assessment of many architectures followed by more detailed assessment of down-selected subsets
- Technical flight system concepts are first mapped to select business models to establish mission cost building blocks
- Missions are implemented as frequently as possible, constrained by the program budget profile
- Architecture performance as measured by availability and other metrics are then assessed

Three Basic Study Tenets for the Program

(from AST Kickoff)

- Sustainability
  - The LI program should provide the *data products* for the long haul, without extraordinary infusions of funds, within the budget guidance provided.
- Continuity
  - The LI program should continue the long term Landsat data record. This does not necessarily mean the imagery per se, but the *usable products* that define the utility of the data record.
- Reliability
  - The LI program should be robust and *not susceptible to single point failures*. The loss of a single satellite or instrument on orbit should not cripple the program or significantly impact users.

Architecture Assessment Starts with Concept Definition



Cost & Schedule Assessment Overview

- Standard Aerospace Independent Cost & Schedule Estimate (ICE/ISE) methodology used
  - Similar to process employed for Decadal Survey Process
  - Launch Vehicle cost provided by KSC LSP
- Costing & Schedule based on analogies within Mission Class
  - Class B analogies include Directed Earth Science spacecraft & instruments
  - Class C analogies include ESSP and MIDEX class spacecraft & instruments
  - Class D assumed include small LEO Earth Science and SMEX class spacecraft & instruments
- Assumptions made relative to potential savings due to commercial practices
  - Savings show potential reduction although final risk assessment of utilizing different practices has not been conducted
- Constrained budget requires that some missions to be stretched to fit budget
  - Varies as a function of the annual funding requirements for each mission

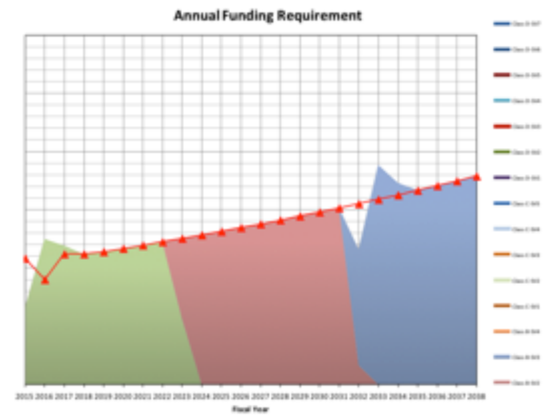
Example of "Sustainability" Impact

- Design to Budget: Due to fixed annual program budget ceiling, schedule is the dependent variable
- This affects the launch cadence and overall system availability.

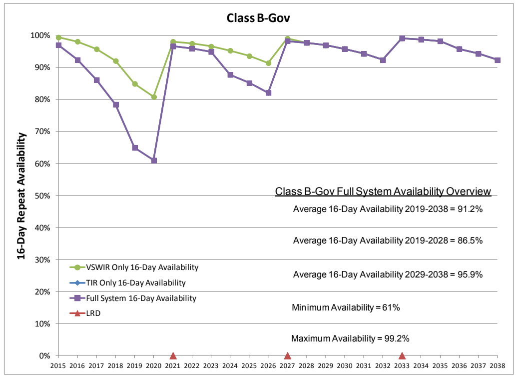
Prior to Fitting Budget

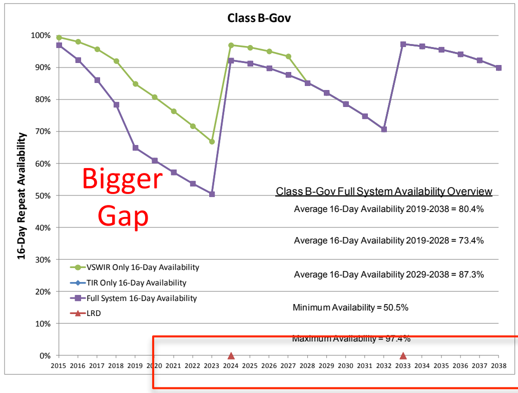
After Fitting Budget

Budget



Availability





Bigger Gap

Fewer Launches

Business Model Trade Space

- Contract Scope Trade Space
  - Combined observatory contract
    - Includes spacecraft and instruments
  - Separate instrument and spacecraft contracts
  - Separate contracts for VSWIR and TIR observatories
  - Bundle flight segment with launch and/or ground/operations
  - Award all instruments to same vendor to maximize efficiency through common parts, electronics, etc.
- Contract Type Trade Space
  - CPAF, Incentives, FFP, FAR Part 15 vs. 12, sole source, AOs, Etc.
- Leveraging Commercial and Relaxed Practice
  - Data Buy
  - Hosted secondary payload
  - Commercial practice s/c and launch
  - More flexible risk classes (C or D)
- Opportunities for technology infusion
  - Including opportunities to support ESD mission portfolio
  - Instrument of opportunity space on Land Imaging spacecraft
  - Demo program in parallel to main program
  - Funded from Land Imaging or rely on ESD ESTO funds?
- International Partnerships
  - Data Sharing
  - Coordinating independent systems
  - Foreign sources as data backup to US system
  - Contributed instruments
  - Hosting US instruments on foreign spacecraft
  - Fly US TIR in formation with foreign satellite
  - Etc.
- Block Buys
  - Block buy of several observatories
    - Contract Type
      - CPAF, FFP, hybrid
  - Separate Reflective and Thermal Satellites Block Buy
  - Block buy of instruments that fly as opportunities emerge
- Launch Options
  - Dedicated launch, shared launch, contributed launch
- Temporal Aspects of Architecture Infusion
  - e.g. Near-Term Thermal Imager Mission followed by a block buy

Business Model Impact on Assessments

- Annual budget constraints of Land Imaging program make choice of business model especially important
- First-order impacts of business models are reflected in architecture cost estimates, which then drive availability results
- Traditional Class B separate procurement approaches (i.e., instruments developed & GFE'd to a spacecraft contractor) provide the lowest risk implementation but at a higher cost
  - Class C & D implementations are also being considered
- Targeted use of commercial practice may enable lower cost, long-life systems without significant increase in risk and deserves further consideration
  - A representative business model Commercial Practice Spacecraft & Launch (CPSL) is used that assumes
    - Government-developed instruments via direct contract or in-house
    - Bundled spacecraft and launch deal that leans heavily on commercial practice
- AST still investigating block buy approaches
- Business model cost impacts estimated based on analogy data

	Gov't Separate Contracts	Comm. Practices S/C & LV
Class B	$$$	$$
Class C	$$	$$
Class D+	$	$

Value Metrics for the AST

- **Consider four value characteristics:**
  1. Performance
  2. Cost
  3. Risk
  4. Added Value
- **Use three phases of screening:**
  1. First phase is intended to filter for architectures that provide continuity and affordability, and are technically ready for implementation
  2. Second phase compares architectures in terms of risk, robustness, and added value
  3. Third phase assess a small number of select architectures in more detail

Value Metrics for the AST – Phase 1

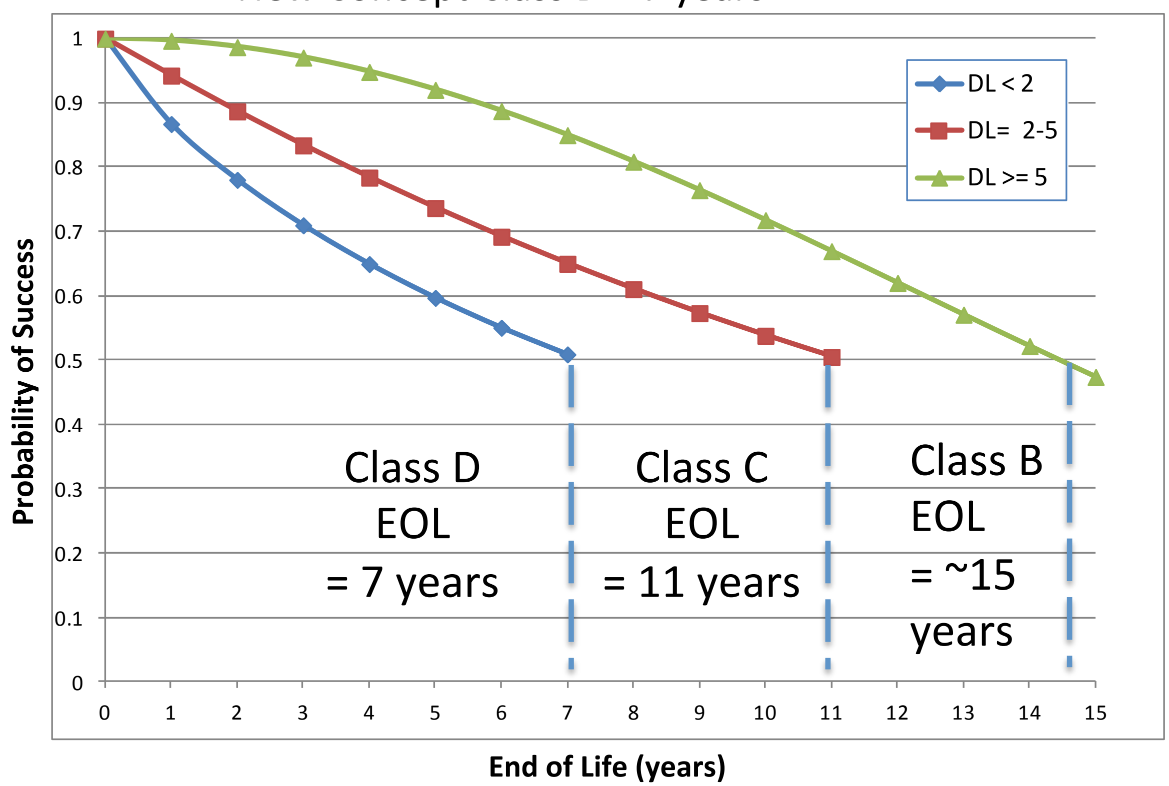
<u>Phase I (Screening)</u>

- *Technology Readiness* –Technology Readiness Level (TRL) of the instrument(s) for the first mission. TRL must be 5 or higher to be considered low risk for this study.
- *Reliability Measure #1 (RM1)* – statistical availability* of 16-day coverage over architecture life. Threshold on RM1 was set to 81% based on historical Landsat program availability.
- *Reliability Measure #2 (RM2)* – statistical availability* of 8-day coverage over architecture life. . Threshold on RM2 was set to 27% based on historical Landsat program availability.

** Availability calculated from historical post-launch reliability data*

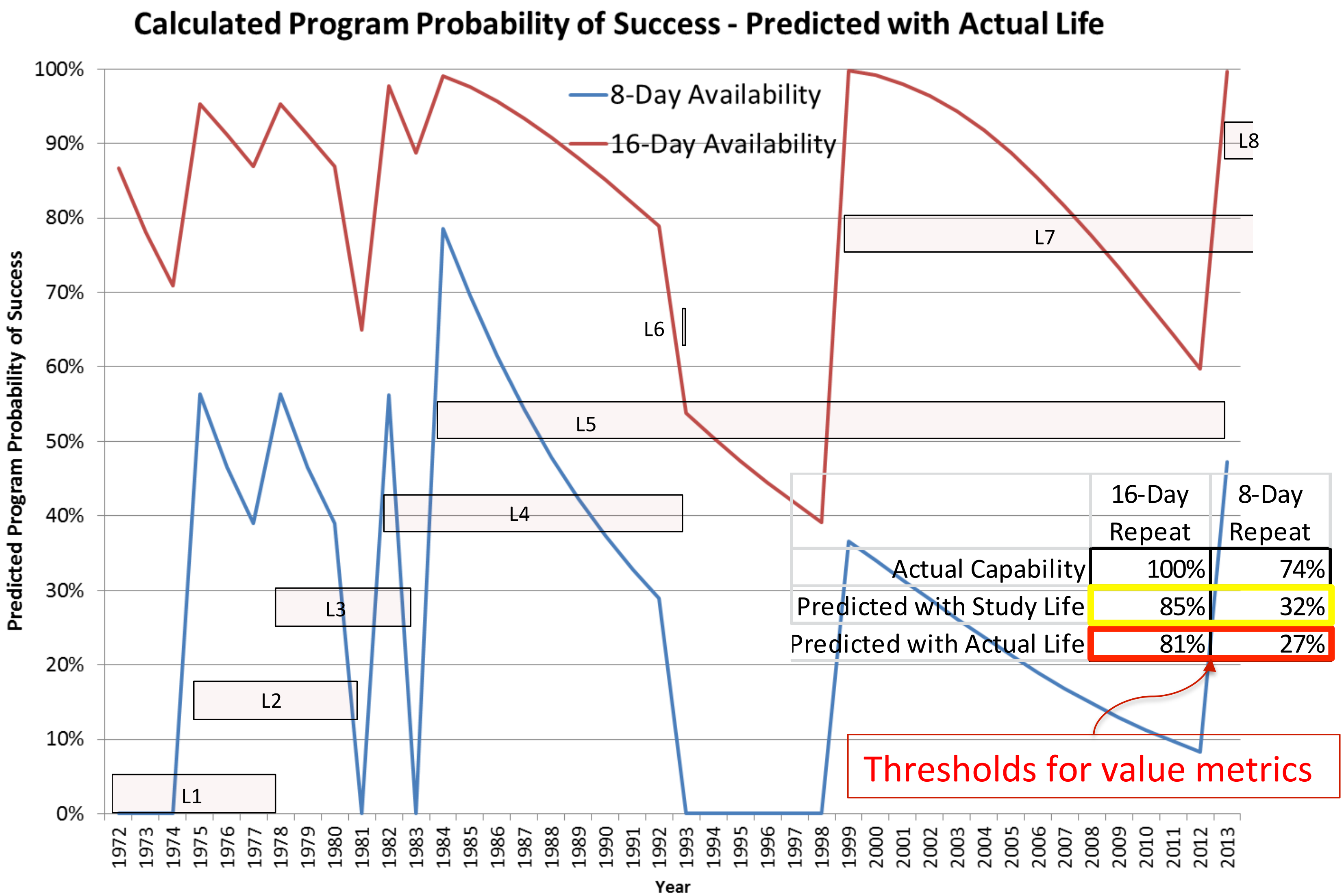
Reliability EOL Assumptions

- AST decided that criteria of 50% Probability of Success (Ps) should signify End of life (EOL) for all candidates
- Historical lifetime results in 50% Ps for:
  - New Concept Class B = 15 years
  - New Concept Class C = 11 years
  - New Concept Class D = 7 years



- Class B
  - 5 year design lifetime
  - Fully redundant system
  - High quality parts
  - Full oversight & review program
- Class C
  - 3 year design lifetime
  - Selective redundancy
  - Some relaxation on parts
  - Oversight & review program
- Class D
  - <2 year design lifetime
  - Single string
  - Mix of part quality with some screening
  - Substantially reduced insight & reviews

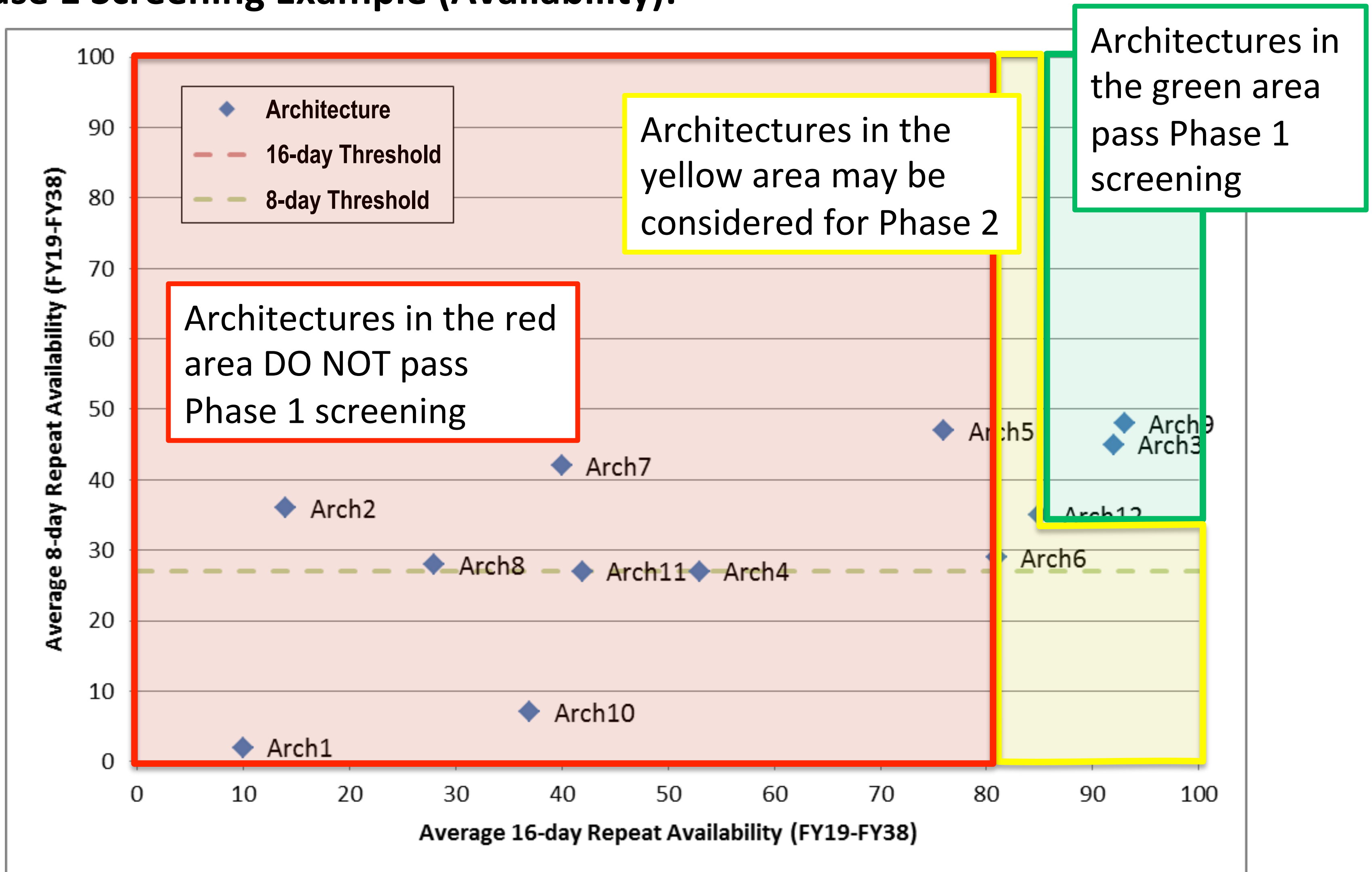
Historical Availability – Calculated Reliability



	16-Day Repeat	8-Day Repeat
Actual Capability	100%	74%
Predicted with Study Life	85%	32%
Predicted with Actual Life	81%	27%

Value Metrics for the AST – Phase 1 Screening

Phase 1 Screening Example (Availability):



Value Metrics for the AST – Phase 2 & 3

<u>Phase 2 Metrics – used for comparison/ranking</u>

- *Likely gap in availability (initial/total; 8, 16-day)*
- *Date of full spectrum capability (US or Int'l)*
- *Date of first US full spectrum capability*
- *"Steady state" launch cadence*
- *Launch failure: average 16-day availability with one launch failure*
- *Launch failure: average 8-day availability with one launch failure*
- *Schedule stretch: for precursor* due to budget constraint
- *Schedule stretch: for "steady state"* due to budget constraint
- *Ground systems / operations impacts* (precursor and steady state)
- *Average Availability for 4-day*

<u>Phase 3 Metrics – used for comparison/ranking</u>

- *Cost risk*
- *Schedule risk*
- *Technical risk*
- *Implementation approach risk*
- *Potential for reduced costs to ESD*
- *Technology infusion*

Value Metrics for the AST – Phase 2 Screening

Phase 2 Screening Example:

Architecture	Initial 8-day Gap (yrs)	Total 8-day Gap (yrs)	Earliest Full Spectrum Capability	First US Full Spectrum Capability	Future Launch Cadence (yrs)	Precursor Schedule Stretch (yrs)	Average Stretch per Mission for Steady State (yrs)	Average RM1 with launch failure (%)	Average RM2 with launch failure (%)	Ground Systems / Ops Impacts – First Mission	Ground Systems / Ops Impacts – Steady State	Risk	Average Availability for 4-day Repeat (%)
Architecture 1	5	8	2024	2024	9	N/A	3	85	60	N/A	L	TBD	0
Architecture 2	3	3	2023	2028	4	1	1	66	28	M	M	TBD	15
Architecture 3	1	2	2021	2021	5	2	2	82	51	L	H	TBD	35

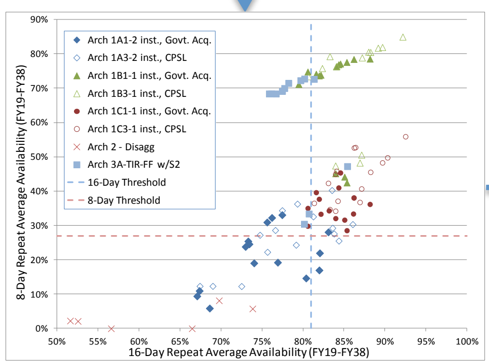
Architecture Downselect Process

> 600 Initial Combinations Defined

> 100 Arch. Selected to "Test Corners"

Assess Architecture Availability

May refine based on Feedback



30 Arch. That Meet Threshold

Filter Through Secondary Metrics

WE ARE HERE

Select Final 3 to 5 Architectures

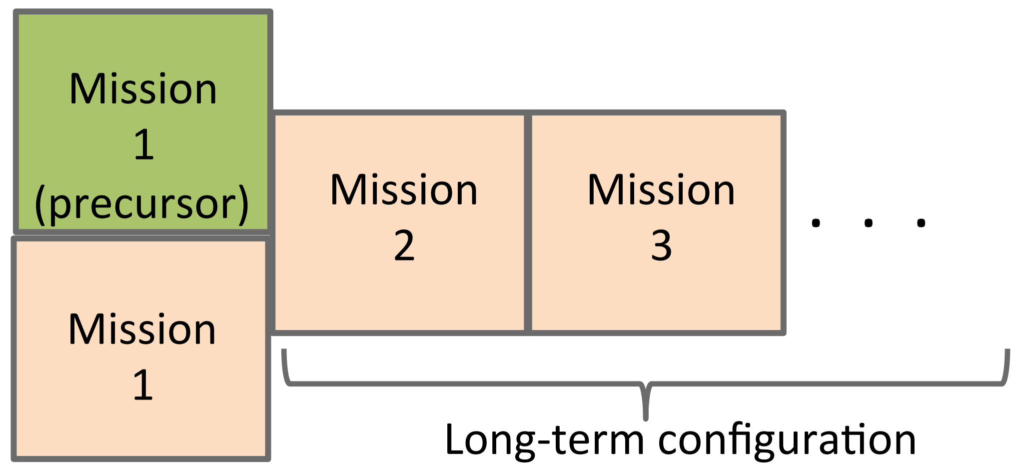
Evan Webb

7. SUMMARY OF INITIAL FINDINGS

What is an Architecture (for the purposes of this study)?

A unique combination over the program lifetime of:

- instrument payload
- spacecraft
- business model/procurement approach
- mission risk class
- organizational partnerships
- launch option
- technology infusion plan
- precursor mission (optional)
    - could be L-8 clone, or other

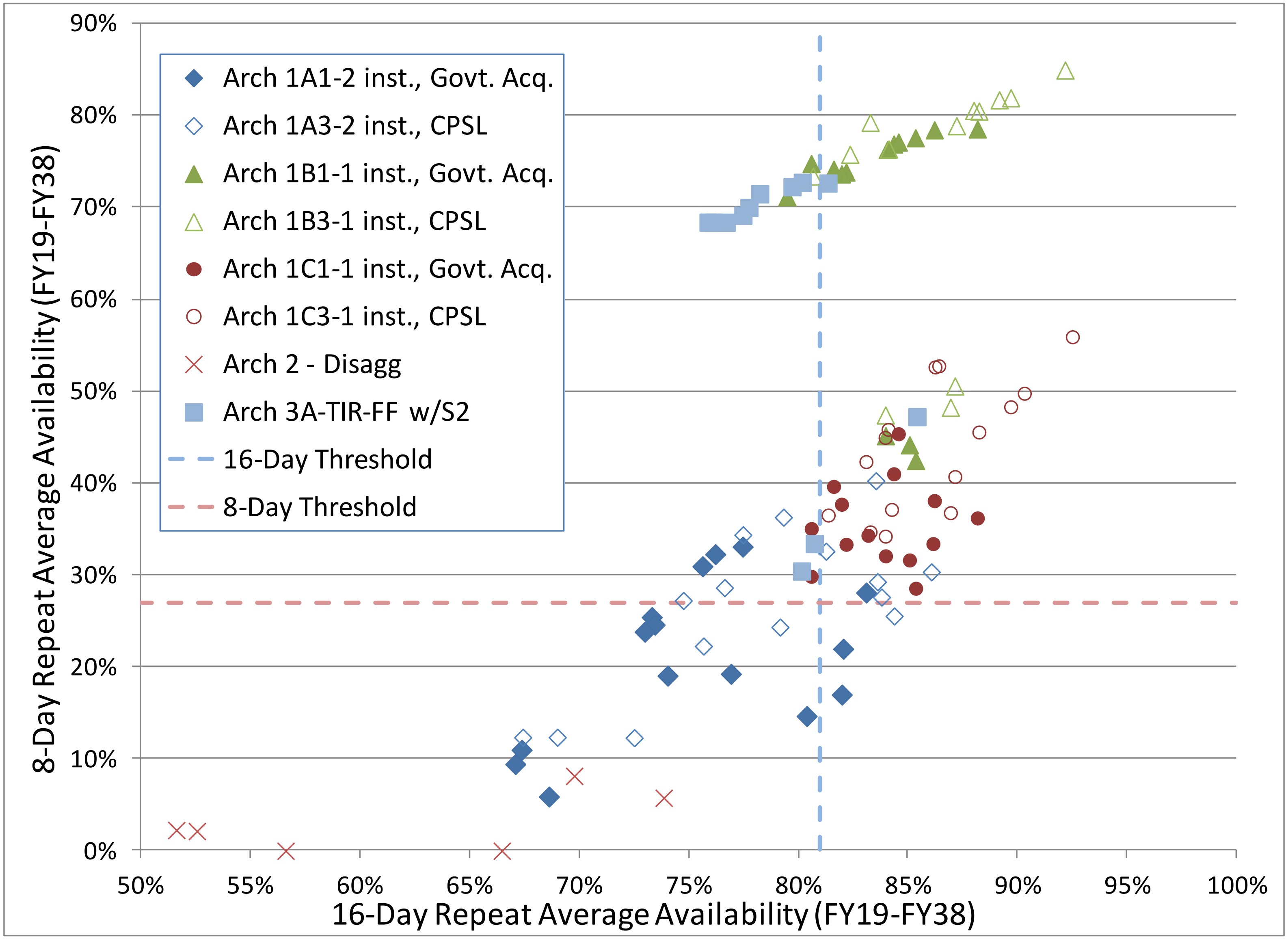


Architecture Trade Space

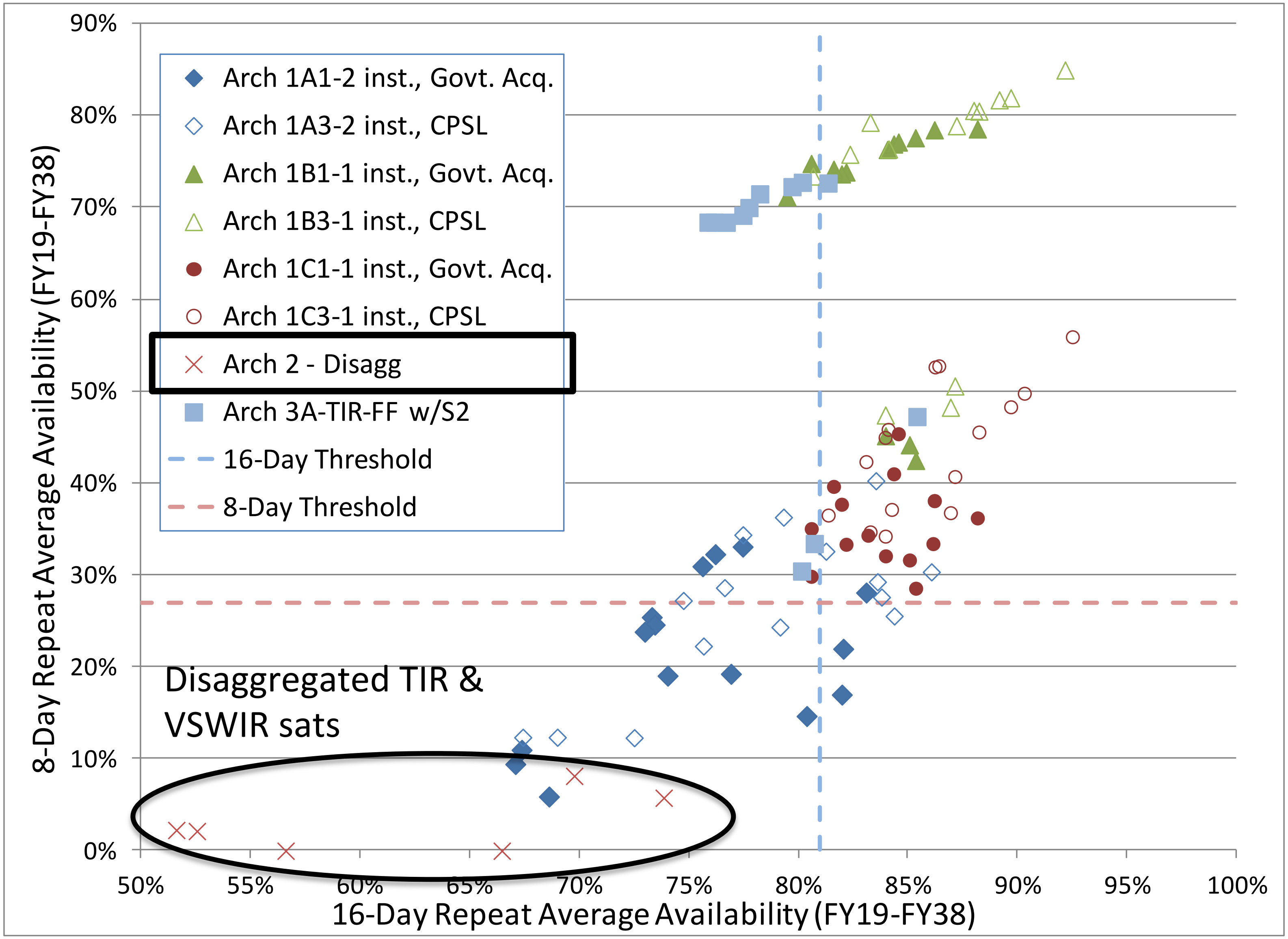
Space-based Systems

Instrument Configuration	Spacecraft Platform	Risk Class	Launch Vehicle	Potential Technology Infusion	Partnerships	Business Models
3+ Separate Instruments	Dedicated Spacecraft	Class B	Dedicated	Hyperspectral	International	Separate Contracts
Two Separate Instruments	Hosted Payload	Class C	Shared	Micro-bolometer	Commercial	Observatory Contract
Combined Instrument	Minisat/ Microsat Constellations	Class D+		Enabling Instrument Technologies	Federal Agencies	Commercial Practices SC + LV
						Hands Off Turn-Key
						Block Buys
						Data Buy
						Sole Source
						IOO Space

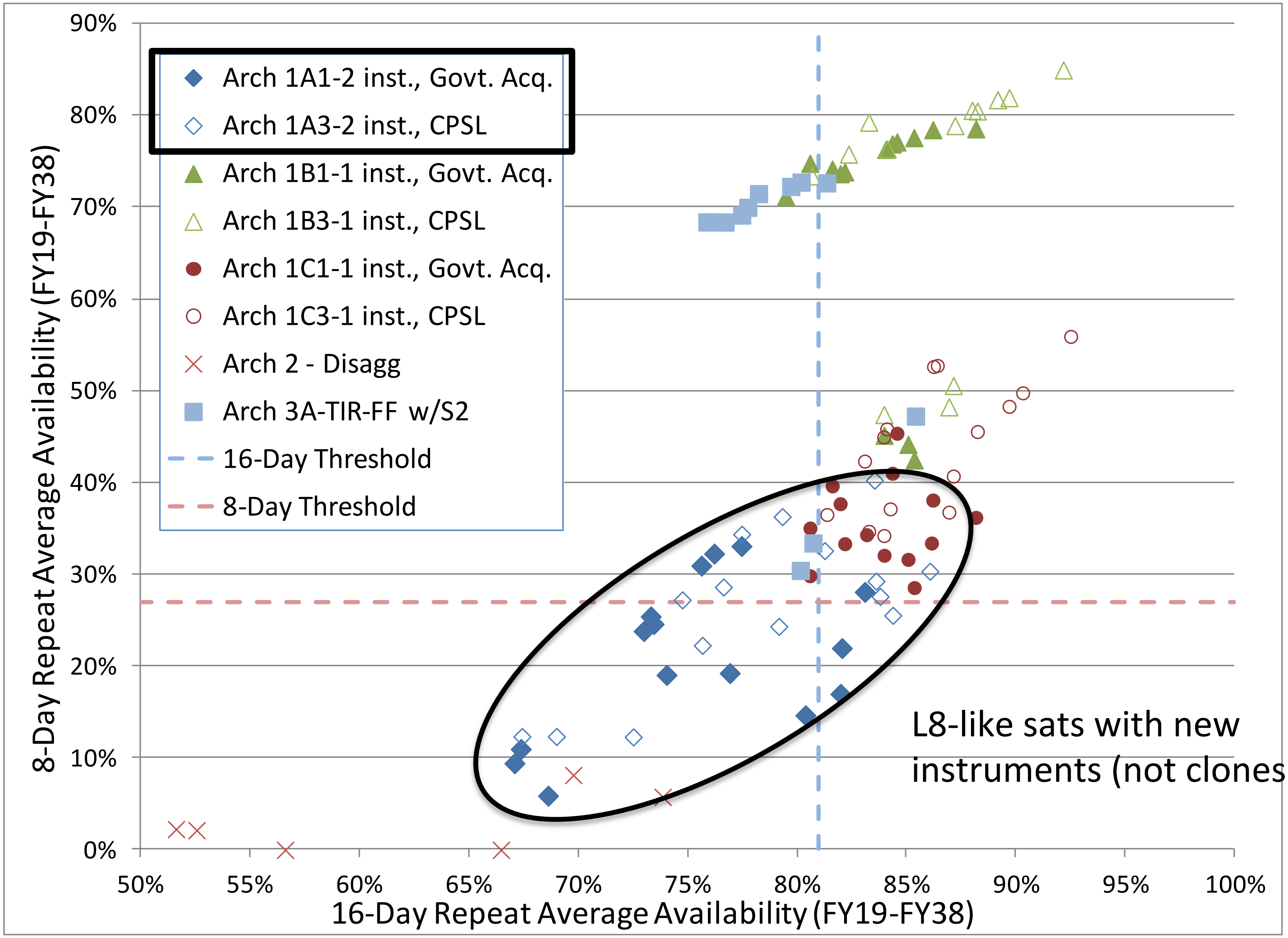
Summary Availability for All Architectures



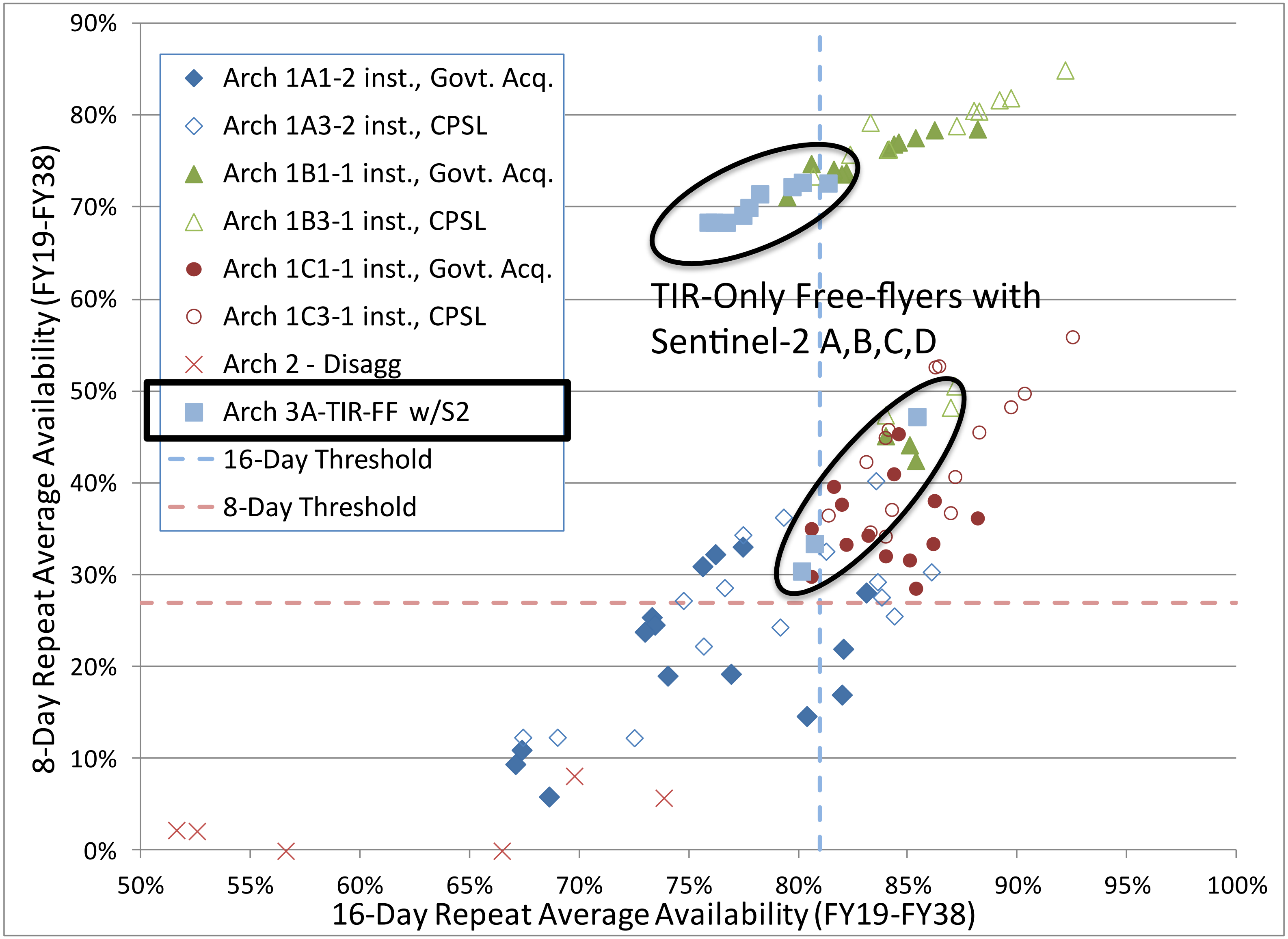
Summary Availability for All Architectures



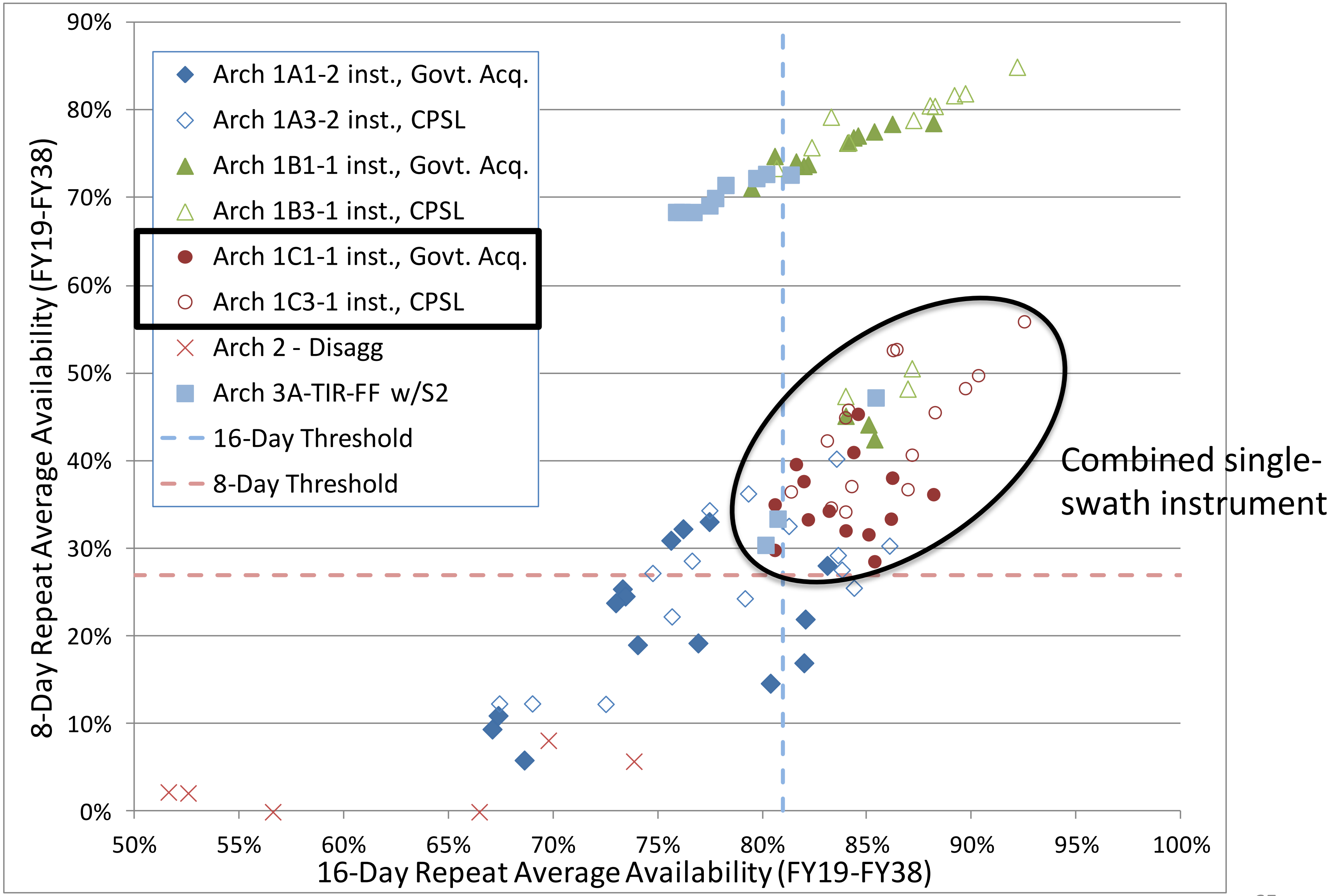
Summary Availability for All Architectures



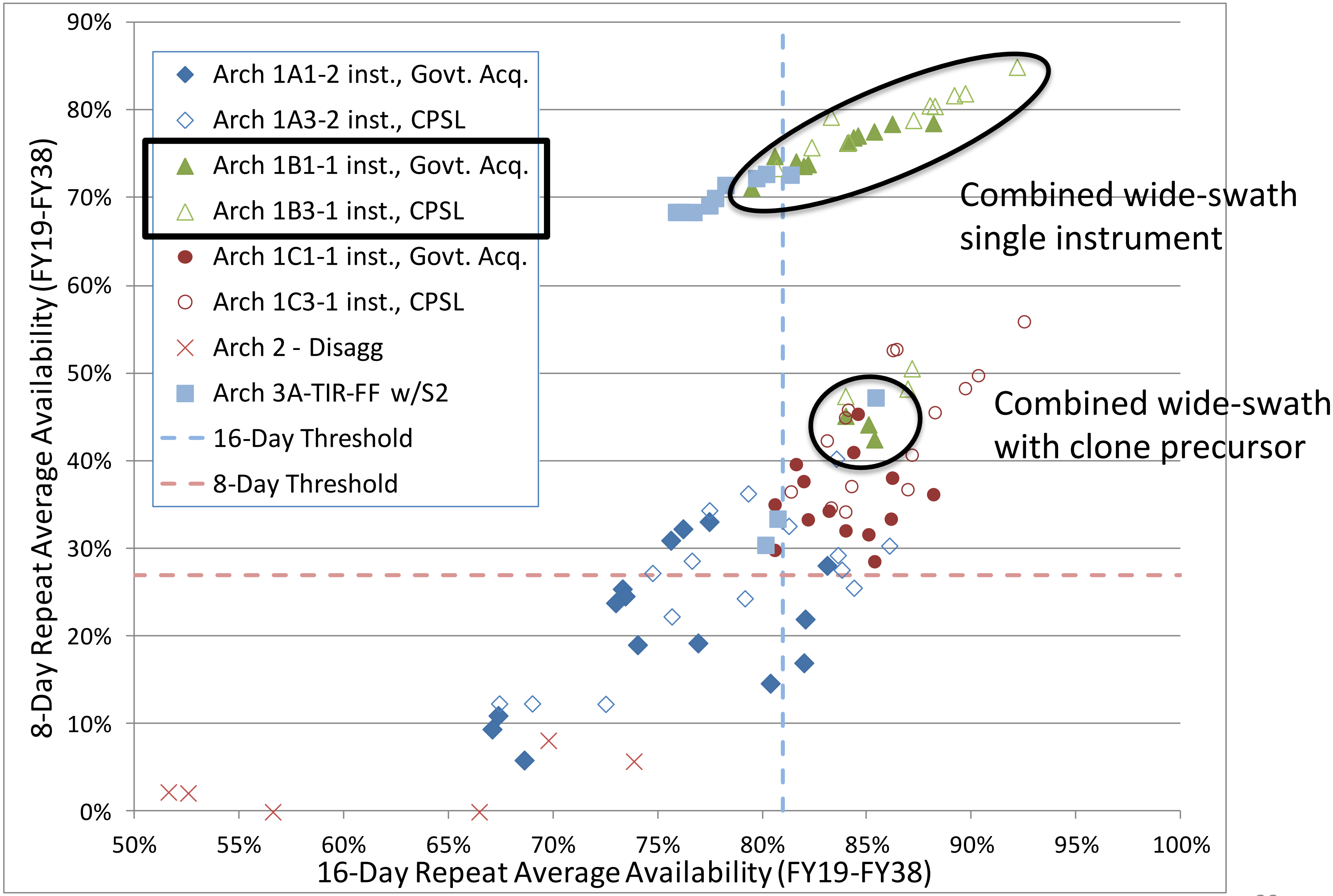
Summary Availability for All Architectures



Summary Availability for All Architectures

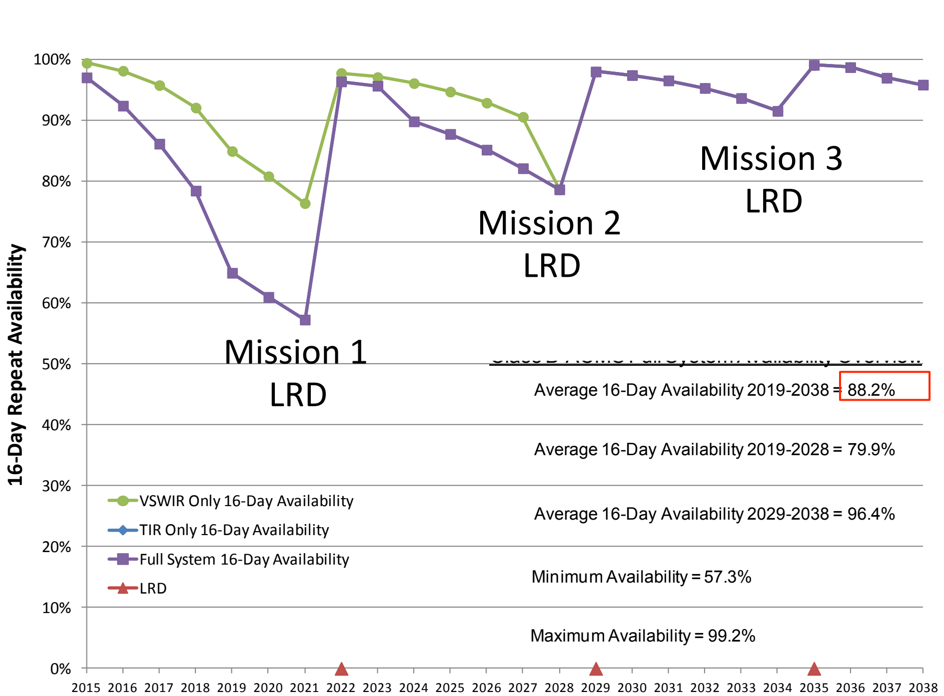


Summary Availability for All Architectures

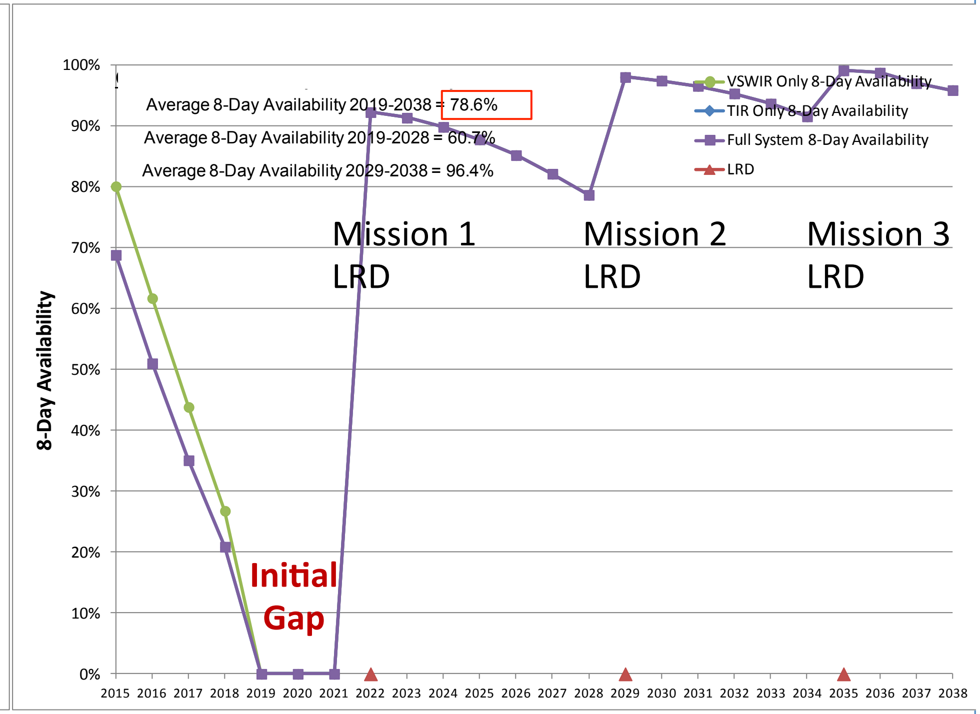


Example Result (1)

16-Day vs. 8-Day Availability – Architecture 1B1
(single satellite full spectrum wide swath), Class B



16-Day Availability

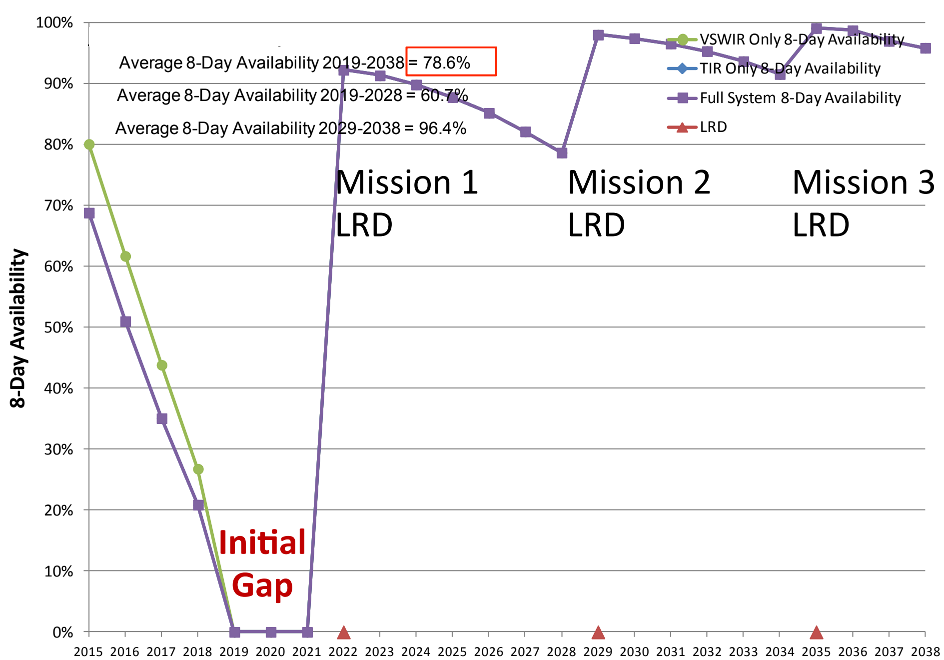


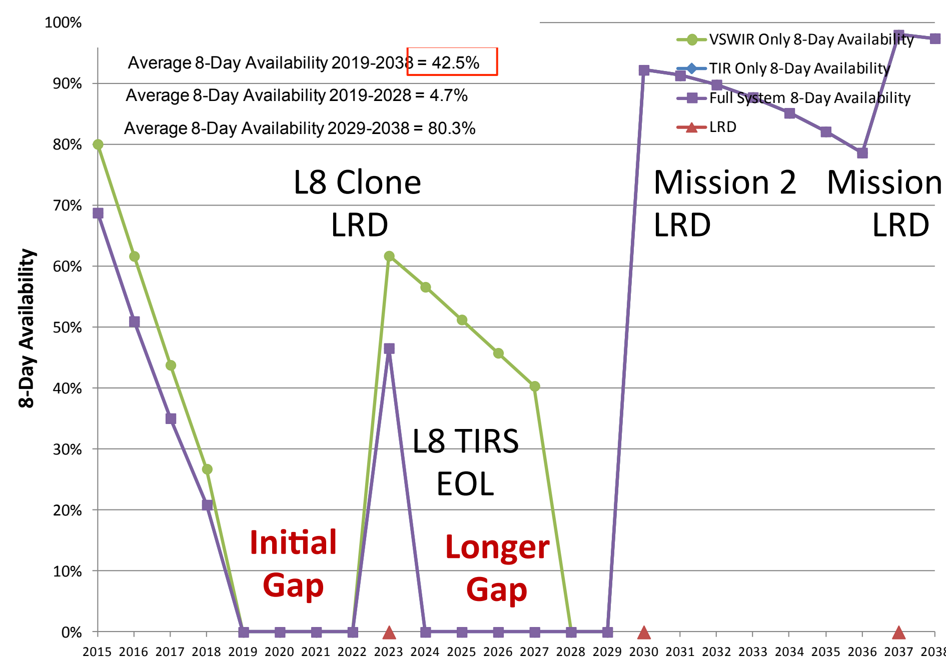
8-Day Availability

* Note: LRD = Launch Readiness Date, EOL = End of Lifetime

Example Result (2)

8-Day Availability – Architecture 1B1, class B, effect of L8 clone Precursor





Without L8 Clone Precursor

With L8 Clone Precursor

The clone precursor takes a long time to develop due to schedule stretch, and then delays LRD #2 as well, likely causing 8-day coverage gaps.

Hypothetical Future Small Satellite Capabilities

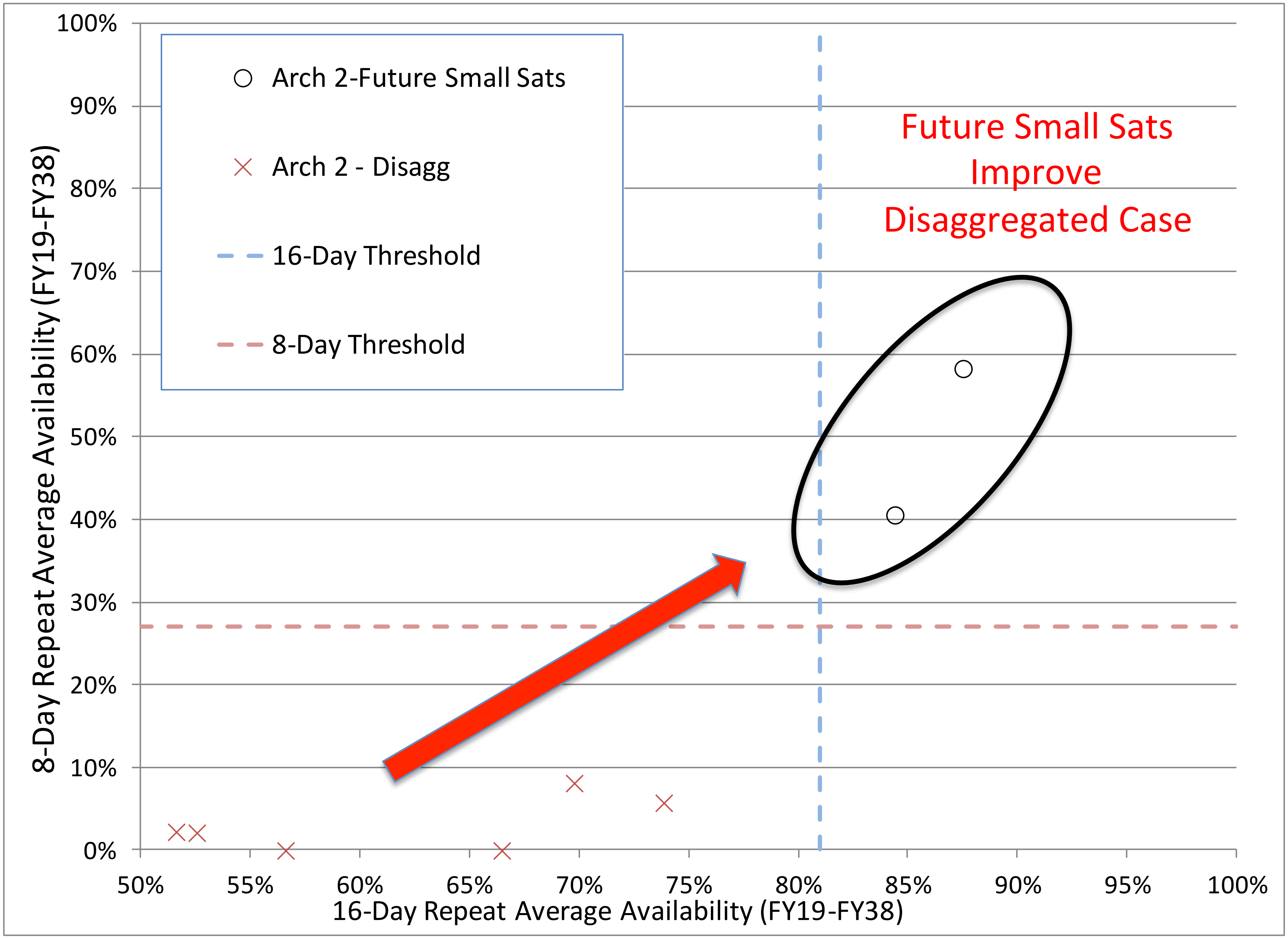
- The AST put together a "what-if" scenario that assumed potential future small satellites with fully capable instruments could be developed in small (50 kg, 100W) constraints to fit within ESPA class (~180 kg) system
  - Assumed characteristics beyond current state of the art for Landsat-like imaging performance

- Two notional concepts identified allowing 2 spacecraft to be launched on single ESPA ring
  - SSa: 2 Separate Instruments on Separate Spacecraft
    - One containing an instrument meeting VSWIR requirements
    - One with instrument meeting TIR requirements
  - SSb: 2 Separate Spacecraft launching Full Spectrum Combined Instrument
    - Provides 2 spacecraft in orbit simultaneously provides consistent 8-day repeat

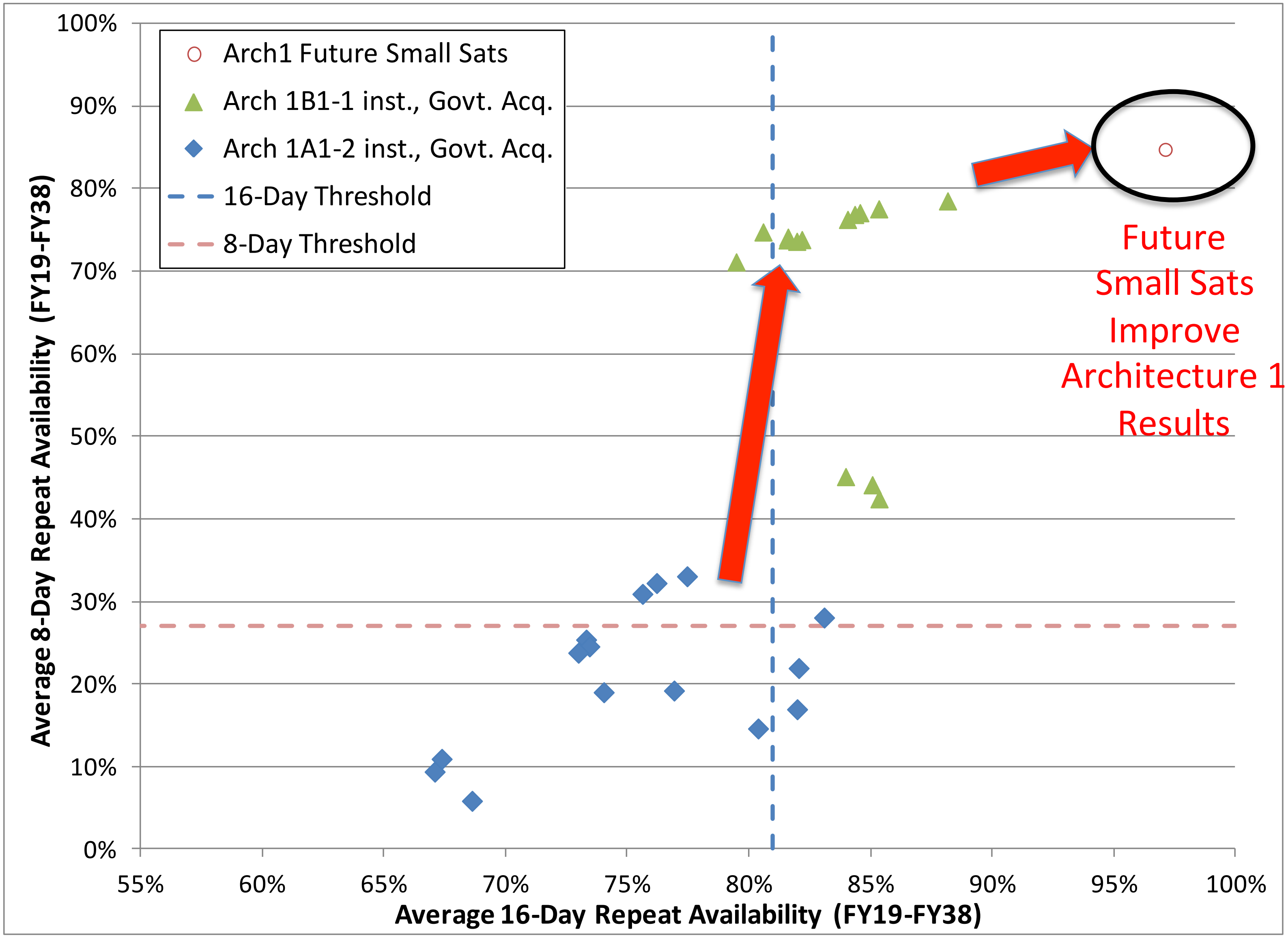
- Low cost allows for 2-year centers in launches for large constellation of spacecraft

- AST recognizes that some technology investment is needed to enable these capabilities

Future Small Satellite Results: Arch 2



Future Small Satellite Results: Arch 1



Observations (1)

- The SLI program budget profile is the dominant driver of the architecture trade space
- AST has identified viable architectures within the constraints of the study
  - However, those approaches that satisfy the value metrics have their own unique drawbacks and risks
    - Landsat 8–like Class B satellites with two instruments, while perhaps lower in technical risk, tend to be expensive and don't fit well in this program budget
    - TIR-only satellites and international partnerships, while lower in cost, rely on foreign systems to continue the U.S. historical Landsat archive
    - A single satellite with double swath coverage (achievable by a scanner, multiple telescopes, etc.), could provide very good performance along with reduced program cost, but may come with some developmental risk

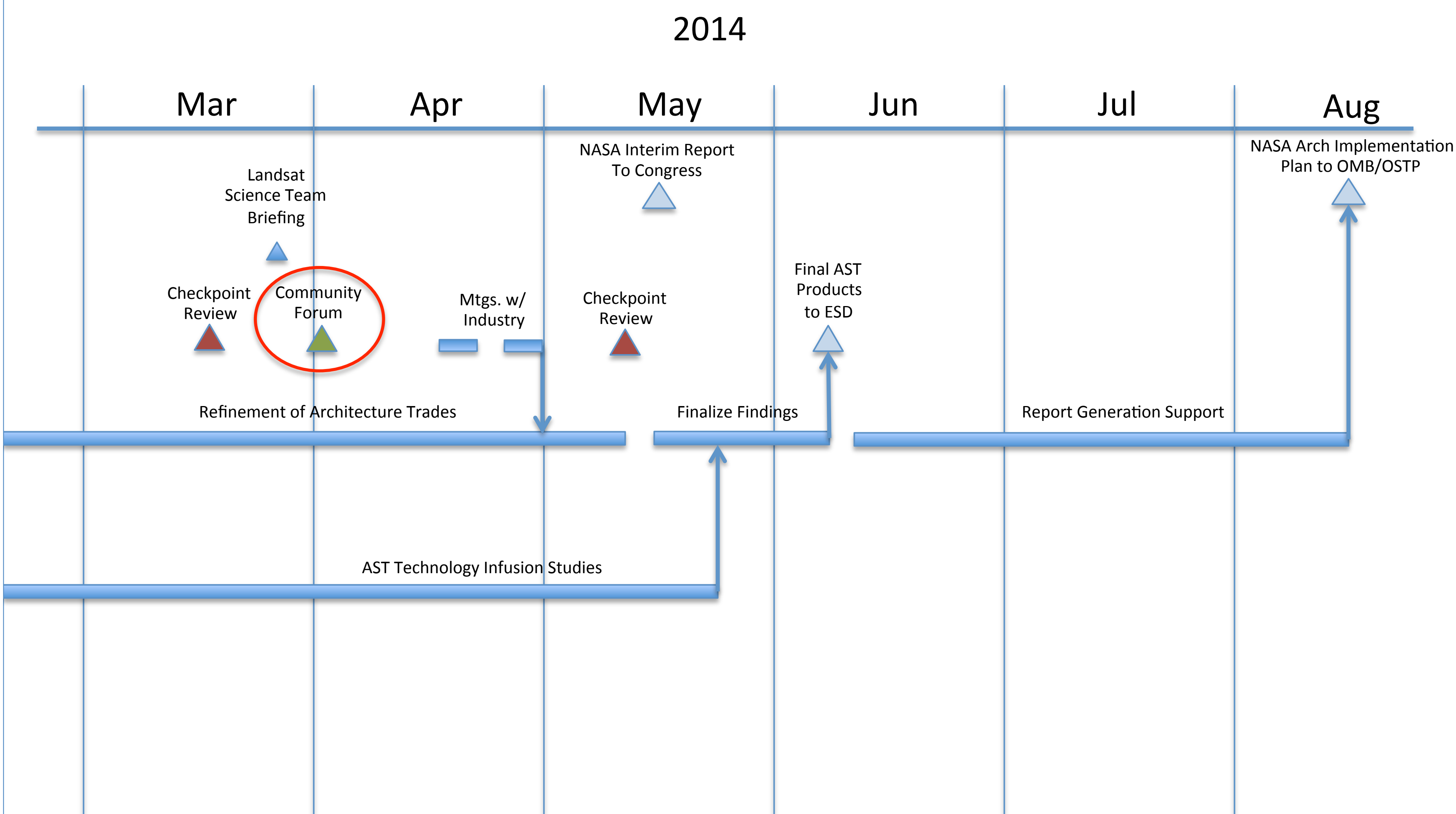
Observations (2)

- Architectures that disaggregate reflective band imagers and thermal imagers onto separate satellites does not perform well in the metrics due to inherent inefficiency
  - Budget profile restricts launch rate to maintain high full-spectrum availability
  - Future small, lower-cost satellites with reduced launch costs may improve performance of this approach
- A “Landsat-8 clone” precursor mission would be a proven performer to maintain very high quality observations, but is expensive enough that launch will be delayed (due to “schedule stretch”) to fit in the budget profile
  - Could be the precursor mission to any of the above approaches
- Future smallsats that could achieve all land imaging requirements in a small fully capable observatory can potentially improve availability substantially in a tightly constrained budget environment

Del Jenstrom – AST Manager

8. REMAINING STUDY PLANS AND INDUSTRY PARTICIPATION

AST Study Timeline & Milestones



Industry Input to AST Studies

- AST would like further industry input to complete studies
  - Seek feedback regarding April 1 forum
    - Send written input to hq-landimaging-rfi@mail.nasa.gov
      - Comments on preliminary AST findings
      - Responses to AST questions (next slide)
  - AST face-to-face meetings with industry and user representatives
    - Provide personal forum for community input
      - ~1 hour per visit
    - Tentatively targeting both west coast and east coast opportunities
      - NASA/ARC: April 15, 16
      - NASA/GSFC: April 29, 30, & May 1
    - One visit per company, please
    - Request date/time via email to hq-landimaging-rfi@mail.nasa.gov

Questions For Industry

- Technical Architectures
  - How best to implement architectures that satisfy the full set of requirements?
  - Do you have other architectures you don't see represented in our studies?
- Business Models
  - How can block buys best be implemented under annual budget constraint?
    - How much does first unit cost increase, and how much can be saved on future units?
    - How can a large cost peak be avoided?
  - How best to reduce cost without unacceptable risk increase?
    - NASA Class A/B/C/D construct equates lower class with lower reliability & lifetime
    - How can SLI Program gain the cost efficiencies of proven industry best practices that can yield high-reliability, long-life systems, specifically with respect to spacecraft and launch services?
      - For example, consider a business model where
        - » Government provided instrument(s) are the prime payload
          - Developed via direct contract or government in-house
        - » Bundled contract for contractor provided/owned spacecraft and launch
          - Developed under streamlined mission assurance requirements
          - Perhaps enables commercial secondary payloads

All

Q&A DISCUSSION

Acronyms

AST – Architecture Study Team
ACMS – Advanced Combined Multispectral Scanner
AWiFS – Advanced Wide Field Sensor
BPT – Baseline Performance Threshold
BRDF – Bi-directional Reflectance Distribution Function
CA – Cloud Aerosol (band)
CBE – Current Best Estimate
CPAF – Cost Plus Award Fee
CPIF – Cost Plus Incentive Fee
CPSL – Commercial Practices Spacecraft & Launch
DL – Design Life
EOL – End of Life
EROS - Earth Resources Observation and Science
ESPA – EELV Secondary Payload Adapter
ESTO – Earth Science Technology Office
ET – Evapotranspiration
ETM+ - Enhanced Thematic Mapper Plus
EV – Earth Venture
FFP – Firm Fixed Price
FPA – Focal Plane Assembly
FOV – Field of View
GSD – Ground Sample Distance
HyspIRI – Hyperspectral Infrared Imager
IDL – Integrated Design Lab
LST – Landsat Science Team
LDCM – Land Data Continuity Mission
LRD – Launch Readiness Date
LV – Launch Vehicle
MPT – Minimum Performance Threshold
MSI – Multispectral Instrument
NEdT – Noise Equivalent delta Temperature
NDVI – Normalized Difference Vegetation Index
NLIR – National Land Imaging Requirements
OAP – Orbit Average Power
OLI – Operational Land Imager
PHyTIR – Prototype HyspIRI Thermal Infrared Radiometer
Ps – Probability of Success
RM – Reliability Measure
ROIC – Read-Out Integrated Circuit
S2 – Sentinel-2
SLI – Sustainable Land Imaging
SNR – Signal-to-Noise Ratio
SSM – Scene Select Mirror
ST – Science Team
SWIR – Short Wave Infrared
TDI - Time Delay Integration
TIR – Thermal Infrared
TIRS – Thermal Infrared Sensor
TRL – Technology Readiness Level
VNIR – Visible and Near Infrared
VSWIR – Visible Shortwave Infrared